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Cyclopedia
of
Applied Electricity

A General Reference Work

ON DYNAMO-ELECTRIC MACHINERY, GENERATORS, MOTORS, STORAGE BATTERIES, ELECTRIC WIRING, ELECTRICAL MEASUREMENTS, ELECTRIC LIGHTING, ELECTRIC RAILWAYS, POWER STATIONS, POWER TRANSMISSION, ALTERNATING CURRENT MACHINERY, TELEPHONY, TELEGRAPHY, ETC.

Prepared by a Corps of

ELECTRICAL EXPERTS, ENGINEERS, AND DESIGNERS OF THE HIGHEST PROFESSIONAL STANDING

Illustrated with over Two Thousand Engravings

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Grateful acknowledgment is here made also for the invaluable co-operation of the foremost engineering firms and manufacturers in making these volumes thoroughly representative of the very best and latest practice in the design, construction, and operation of electrical machinery and instruments; also for the valuable drawings, data, suggestions, criticisms, and other courtesies.

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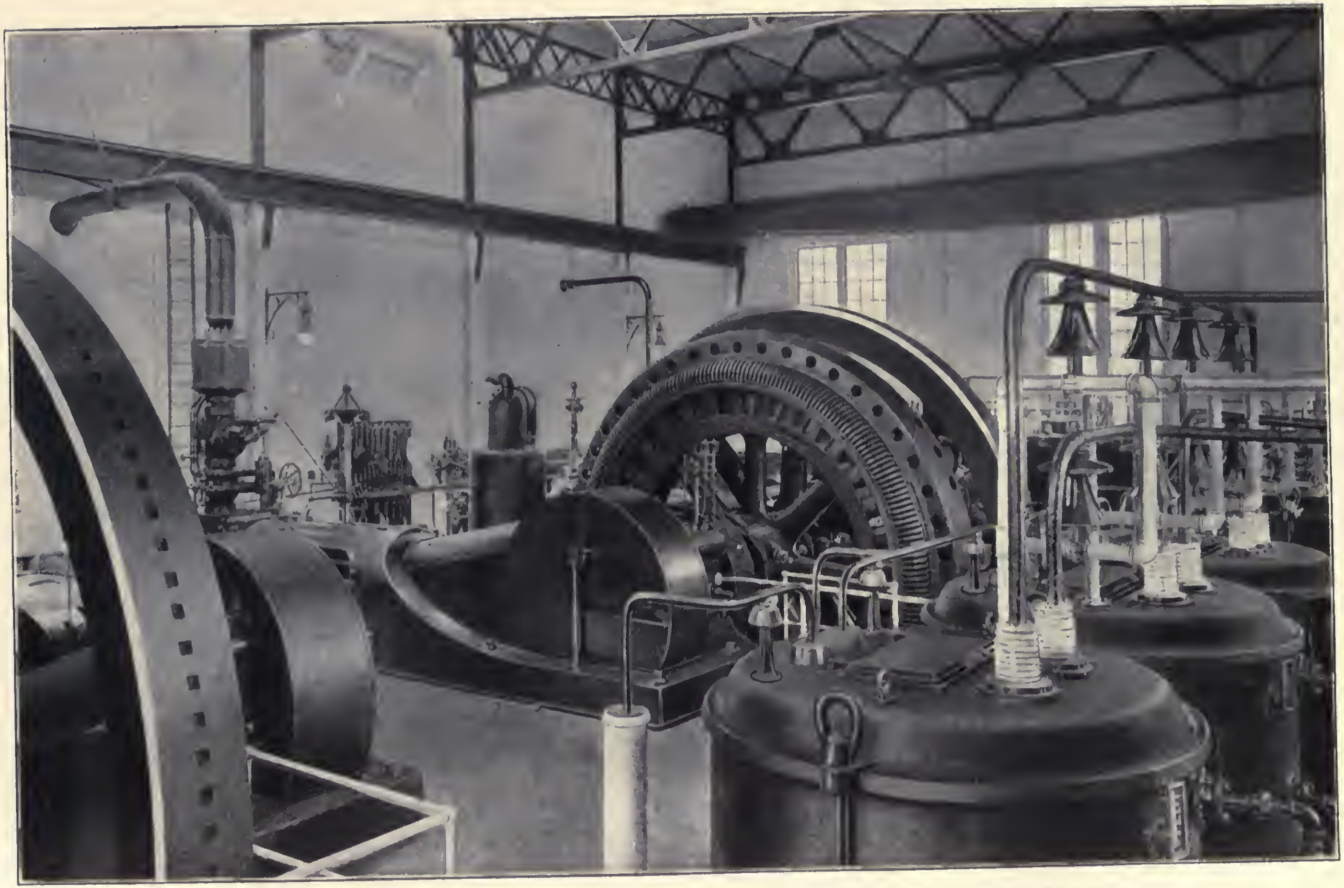

ENGINE-DRIVEN GENERATING UNIT AND TRANSFORMERS FOR ALTERNATING CURRENT
Allis-Chalmers Co., Milwaukee, Wis.

Foreword

IN view of the great need for a more scientific knowledge of electricity by thousands of practical men of limited technical education, an attempt has been made in the following pages to give a presentation of the subject which will be easily understood by such men, and at the same time cover all essential principles and methods. The principles usually deduced by higher mathematics are here made clear by careful explanation and a large number of diagrams drawn especially to supplement and elucidate the text. Numerous engravings exemplify modern practice, and form a pictorial index to the latest and best methods of applying electricity to lighting, railways, power transmission, the driving of machine tools, etc.

¶ The Cyclopedia of Applied Electricity is based upon the method which the American School of Correspondence has developed and successfully used for many years in teaching practical electricians the scientific principles underlying their work. It is a compilation of representative Instruction Papers of the School, and forms a simple, practical, concise, and convenient reference work for the shop, the library, the school, and the home.

¶ The success which the American School of Correspondence has attained in teaching thousands of electricians, is in itself the best possible guarantee for the present work. Therefore, while these volumes are a marked innovation in technical literature—representing as they do the best ideas and methods of a large number of different authors, each an acknowledged authority in his work—they are by no means an experiment, but are in fact based on what has proved itself to be the most successful method yet devised for the education of the busy working man.

¶ Among the sections of especial timeliness are those on Alternating-Current Machinery, Storage Batteries, Electric Wiring, Lighting, etc. In these pages the authors have succeeded in presenting the subjects in such manner as to overcome the hitherto insurmountable obstacle—higher mathematics. The rules and formulæ are presented in a very simple manner, and special effort has been made to illustrate every principle by diagrams, curves, and practical examples.

¶ Numerous examples for practice are inserted at intervals; these, with the test questions, help the reader to fix in mind the essential points, thus combining the advantages of a textbook with those of a reference work.

¶ Grateful acknowledgment is due to the corps of authors and collaborators who have prepared the many sections of this work. The hearty co-operation of these men—engineers of wide practical experience, and teachers of acknowledged ability—has alone made these volumes possible.

¶ The Cyclopedia is published in the belief that it will meet a real need among designers, constructors, and operators of electrical machinery. That it may save many weary hours of search among the scattered textbooks and reference works of the day—books which, being intended largely for college-trained men, are necessarily far from meeting the needs of the average practical man—is the hope of the compilers and publishers.

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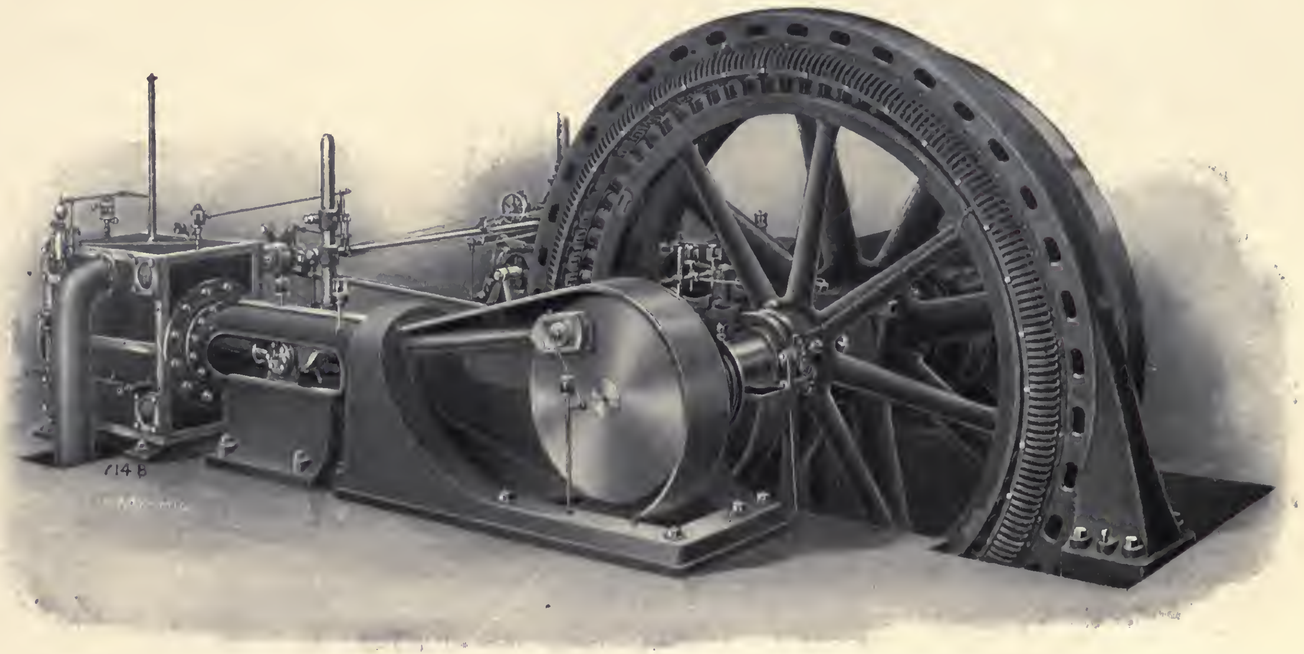

NATIONAL ENGINE-TYPE ALTERNATOR.

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ALTERNATING CURRENT MACHINERY.

PART I.

THE SIMPLE ALTERNATOR.

Alternating Electromotive Forces and Currents

1. Definitions. The **alternator** is an arrangement by means of which mechanical energy is used to cause the magnetic flux from a magnet to pass through the opening of a coil of wire first in one direction and then in the opposite direction. This varying magnetic flux induces an electromotive force in the coil, first in one direction and then in the other. This electromotive force, called an **alternating electromotive force,** produces an **alternating current** in the coil, and in the circuit which is connected to the terminals of the coil.

In the common type of alternator, the above-mentioned magnet and coil move relatively to each other. Fig. 1 shows the essential features of such an alternator. The poles N, S, N, S, etc., of a multipolar magnet called the **field magnet,** project radially inwards toward the passing teeth *a a a* of a rotating mass A of laminated iron; and upon these teeth are wound coils of wire *c c*, in which the alternating electromotive force is induced. The rotating mass of iron with its windings of wire is called the **armature.** On the armature shaft (not shown in the figure), at one end of the armature, are mounted two insulated metal rings *r r*, called **collecting rings.** These metal rings are connected to the ends of the armature winding, and metal brushes *b b* rub on these rings, thus keeping the ends of the armature winding in continuous contact with the terminals of the external circuit to which the alternator supplies alternating current. No external circuit is shown in the figure.

The electromotive forces induced in adjacent armature coils are in opposite directions at each instant, and the coils are so connected together that these electromotive forces do not oppose each other. This is done by reversing the connections of every alternate coil, as indicated by the dotted lines connecting the coils in Fig. 1. The electromagnetic action of this type of alternator depends only upon the *relative* motion of field magnet and armature, and large machines are often built with stationary armature and revolving field magnet. In the type of machine illustrated in Fig. 1, the armature revolves while the field magnet is stationary. This type, called the **revolving-armature** type, is generally adopted in small alternators.

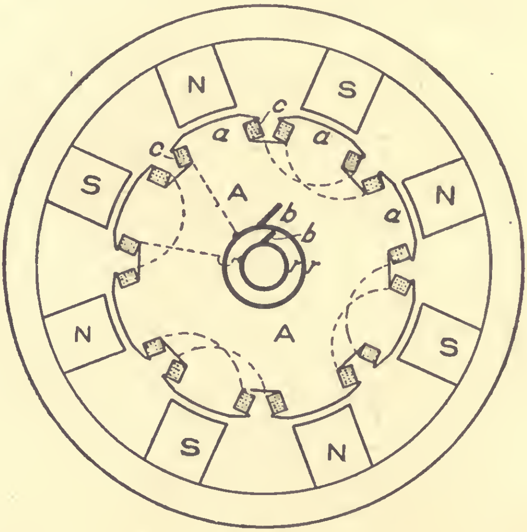

Fig. 1.

The field magnet of an alternator is usually an electro-magnet which is excited by a continuous electric current supplied by an independent generator, generally by an auxiliary continuous-current dynamo, called the **exciter.** The exciting current flows through coils of wire wound on the projecting poles N, S, N, S of the field magnet. These coils are not shown in Fig. 1.

Armature Cores and Armature Windings. The type of armature core shown in Fig. 1 is called the **toothed** armature core; and the winding is said to be **concentrated**—that is, the armature conductors are grouped in a few heavy bunches. Armature cores are also made with many small slots, in which the armature conductors are grouped in small bunches. This type of core is called a **multi-slotted** core, and the winding is said to be **distributed.** The various types of armature windings are described farther on.

In some of the earlier types of alternators the armature core consisted of a smooth, cylindrical mass of laminated iron, upon the face of which the conductors were arranged in bands side by side, one layer or more in depth. This type of armature is called the **smooth-core** armature.

2. Cycle, Frequency, and Period. The electromotive force of an alternator passes through a set of *positive* values while a given coil of the armature is passing from a south to a north pole of the field magnet, and through a similar set of *negative* values while the coil is passing from a north to a south pole. The complete set of values, including positive and negative, through which an alternating electromotive force (or alternating current) repeatedly passes, is called a **cycle.** The number of cycles per second is called the **frequency.**

The fractional part of a second occupied by one cycle is called the periodic time, or **period,** of the alternating electromotive force or current.

Let f be the frequency in cycles per second, and T the periodic time expressed as a fraction of a second. Then

$$f = \frac{1}{T}. \qquad (1)$$

Example. If an alternating current has a frequency of 60 cycles per second, the period, T, of one cycle is one-sixtieth of a second.

Specification of Frequency in Terms of the Number of Alternations or Reversals in a Given Time. Frequency is sometimes expressed by stating the number of alternations or reversals per minute. For example, an alternator having a frequency of 133 cycles per second has 266 reversals or alternations per second, or 16,000 alternations per minute. Frequencies are sometimes specified in alternations per minute, but specification in cycles per second is the more usual practice and is preferable. Cycles per second = alternations per minute ÷ (2 × 60).

3. Relations between Speed and Frequency. Let p be the number of poles of the field magnet of an alternating-current machine; let n be the speed of its armature in revolutions per minute; and let f be the frequency of its electromotive force in cycles per second. Then

$$f = \frac{p}{2} \times \frac{n}{60}. \qquad (2)$$

Examples. 1. A certain alternator has 10 poles, and runs at 1,500 revolutions per minute. What is its frequency?

Solution. Substituting 10 for p, and 1,500 for n, in equation 2, we have

$$f = \frac{10}{2} \times \frac{1500}{60} = 125 \text{ cycles per second.}$$

2. An alternator is to run at 600 r. p. m. (revolutions per minute) and is to give a frequency of 60 cycles per second. What number of poles is required?

Solution. Solving equation 2 for p, we have

$$p = \frac{2 \times 60 \times f}{n},$$

from which, substituting $f = 60$, and $n = 600$, we have

$$p = \frac{2 \times 60 \times 60}{600} = 12 \text{ poles.}$$

4. Advantages and Disadvantages of Alternating Currents. The electric transmission of a given amount of power may be accomplished by a large current at low electromotive force, or by a small current at high electromotive force. In the first case very large and expensive transmission wires must be used, or the loss of power in the transmission line will be excessive. In the second case comparatively small and inexpensive transmission wires may be used. Thus it is a practical necessity to employ high electromotive forces in long-distance transmission of power.

Example. It is desired to transmit 1,000 kilowatts of power over a distance of 10 miles, supposing that a loss in the line of 10 per cent of the power delivered is considered permissible. This corresponds to 100 kilowatts loss.

Solution.—CASE 1. Suppose that the electromotive force at the receiving end of the line is to be 100 volts. Then the current would be 1,000,000 watts divided by 100 volts, or 10,000 amperes. The resistance of the line must be such that the watts lost in the line—namely 100,000 watts—would be equal to RI^2, so that the resistance R of the line must be $\frac{W}{I^2}$, or 0.001 ohm. This would require two transmission wires each 10 miles long and 33 inches in diameter, or a total weight of 175,000 tons of copper, which would cost about $52,500,000.

Case 2. Suppose that the electromotive force at the receiving end of the line is to be 1,000 volts. Then the current would be 1,000,000 watts divided by 1,000 volts, or 1,000 amperes. The resistance of the line must be such that the watts lost in the line—namely, 100,000 watts—would be equal to RI^2, so that the resistance R of the line must be 0.1 ohm. This would require two transmission wires, each 10 miles long and 3.3 inches in diameter, or a total weight of 1,750 tons of copper, which would cost about $525,000.

Case 3. Suppose that the electromotive force at the receiving end of the line is to be 10,000 volts. Then the current would be 1,000,000 watts divided by 10,000 volts, or 100 amperes. The resistance of the line must be such that the watts lost in the line—namely 100,000 watts—would be equal to RI^2, so that the resistance R of the line must be 10 ohms. This would require two transmission wires, each 10 miles long and 0.33 inch in diameter, or a total weight of 17.5 tons of copper, which would cost about $5,250.

These results are summarized in the following table:

TABLE I.

Size and Cost of Copper Wire.

To transmit 1,000 kilowatts a distance of 10 miles (one way) with a line loss equal to 10 per cent of the power delivered, for three different values of electromotive force.

Volts at receiving end of line. (E)	Amperes in line. (I)	Ohms in line. (R)	Diameter of wire, in inches.	Weight of wire, in tons.	Cost of line copper, in dollars.
100	10,000	0.001	33	175,000	52,500,000
1,000	1,000	0.1	3.3	1,750	525,000
10,000	100	10.0	0.33	17.5	5,250

High electromotive forces are dangerous under the conditions that ordinarily obtain among users of electric light and power; and many types of apparatus, such as incandescent lamps, operate satisfactorily only with medium or low electromotive forces. Therefore means must be provided, at a receiving station, for transforming the power delivered, from high electromotive force and small current to low electromotive force and large current, if long-distance transmission is to be successful. This is called **step-down transformation.** The advantage of the alternating current over the direct current lies almost wholly in the cheapness of construction and of operation, and in the high efficiency of the alternating-current as compared with the direct-current apparatus that is required for transformation.

In step-down transformation of direct current, a motor takes a small current from the high-electromotive-force transmission mains, and drives a dynamo which delivers large current to service mains at low electromotive force. This apparatus, or its equivalent, the **dynamotor,** is expensive to construct; it requires attention in operation; and its efficiency is never, perhaps, above 90 per cent.

The step-down transformation of alternating currents is accomplished by means of the **alternating-current transformer,** which is described later on. The alternating-current transformer is very much cheaper than a dynamo and motor of the same output; it requires no attention in operation; and its efficiency under full load is usually greater than 97 per cent, especially in large sizes.

The alternating current has some minor advantages over the direct current on account of the fact that alternating-current machines are frequently simpler in construction than direct-current machines. In particular, the commutator is not an essential part of an alternating-current machine. In the case of the inductor alternator and the induction motor, again, the rotating part may not have any sliding electrical contacts whatever.

The simple single-phase alternating current is not very well suited to motor service. The single-phase alternating-current motor does not start satisfactorily in the case of large machines. although self-starting single-phase motors up to perhaps 20 horsepower are in commercial use, where neither direct-current nor polyphase alternating-current machines are available. For uninterrupted service the synchronous motor is frequently used, the starting being effected by an auxiliary engine or other independent mover. The synchronous motor is described in subsequent pages.

The synchronous motor is not satisfactory when frequent starting is necessary. For such service the induction motor is used. The induction motor also is described later on. The simple induction motor, to start satisfactorily, must be supplied with two or more distinct alternating currents transmitted to the motor over separate lines. This is called the **polyphase** system of transmission, and is reserved for full treatment in later pages.

For some purposes, especially for the electrolytic processes used on a large scale in electro-chemical works, only direct current can be used. When power transmitted by alternating current is to be delivered in the form of direct current, the conversion is effected by means of the **rotary converter,** also described below.

5. Characteristic Features of Alternating-Current Problems.* In direct-current work the electrical engineer is concerned with the relations between electromotive force, resistance, current, and power. These relations are determined by the applications of the following laws:

Power Law.

$$P = E\,I, \qquad (3)$$

in which P is the total power in watts delivered to a circuit by a generator of which the terminal electromotive force is E volts, when it produces a current of I amperes.

Ohm's Law.

$$I = \frac{E}{R}, \qquad (4)$$

in which I amperes is the steady current produced by E volts acting on a circuit of R ohms resistance.

Joule's Law.

$$P = R\,I^2, \qquad (5)$$

in which P is the power in watts expended in heating a circuit of R ohms resistance, when a current of I amperes is forced through the circuit.

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* Note. For definitions and explanations of the new terms used in this article, see later paragraphs, also the succeeding discussion on "Harmonic Electromotive Forces and Currents."

Kirchhoff's Laws.

1. When a circuit branches, the current in the main circuit is equal to the sum of the currents in the separate branches.

2a. When two or more sources of electromotive force are connected in series, the total electromotive force is the sum of the individual electromotive forces.

2b. When an electromotive force acts on a number of elements or things in series, it is subdivided into parts, each of which acts upon one of the elements, and the sum of these parts is equal to the total electromotive force. For example, an arc-light dynamo of which the terminal electromotive force is 3,000 volts, acts on 60 similar arc lamps connected in series. Neglecting the resistance of the connecting wires, each lamp is acted upon by one-sixtieth of the total electromotive force, or by 50 volts.

In alternating-current work the electrical engineer is likewise concerned with the relations between electromotive force, resistance, current, and power. These relations are determined by the application of the same fundamental laws as in case of direct currents, but in more or less modified forms.* A summary of the fundamental laws of alternating currents is here given simply for purposes of comparison:

Power Law, for Alternating-Current Circuits.

$$P = E\,I \cos\theta, \qquad (6)$$

in which P is the power in watts delivered to a circuit by an alternator of which the "effective" terminal electromotive force is E volts, when it produces an "effective" current of I amperes in a circuit, and Cos θ is what is called the "power factor" of the circuit.

Ohm's Law, for Alternating-Current Circuits.

$$I = \frac{E}{\sqrt{R^2 + X^2}} \qquad (7)$$

in which I is the "effective" current in amperes produced by an

---

* NOTE. These modifications of the fundamental laws and the meaning of the unfamiliar terms here used, are fully discussed and explained at the end of this chapter and in the succeeding chapter; and the student is not expected to understand fully the reasons for the statements here given, until he has completed the first two chapters.

"effective" electromotive force of E volts acting on a circuit of which the resistance is R ohms, and the "reactance" is X ohms.

Joule's Law, for Alternating-Current Circuits.

$$P = R I^2, \qquad (5)$$

in which P is the power in watts expended in heating a circuit of R ohms resistance when an "effective" alternating current of I amperes is forced through the circuit.

Kirchhoff's Laws, for Alternating-Current Circuits.

1. When an alternating-current circuit branches, the "effective" current in the main circuit is the "geometric"* (or "vector") sum of the "effective" currents in the separate branches.

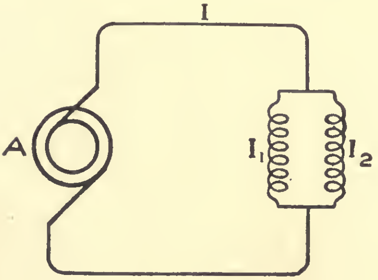

Fig. 2*a*.

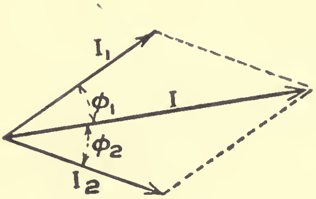

Fig. 2*b*.

Example. An alternator A, Fig. 2*a*, supplies an effective current of I amperes in the main circuit, which divides into two branches. The effective currents in the two branches are I_1 and I_2 amperes respectively. The relation between I, I_1, and I_2 is shown in Fig. 2*b*. The angles ϕ_1 and ϕ_2 depend upon the relative values of the resistance and reactance of the respective branches, as is explained later. It is to be particularly noticed that the arithmetical sum of I_1 and I_2 is in general greater than I.

2a. When two or more alternators (or transformer secondaries) are connected in series, the total effective electromotive force is the "geometric" (or "vector") sum of the effective electromotive forces of the individual alternators.

Example. Two alternators A_1 and A_2, Fig. 3, of which the effective electromotive forces are E_1 and E_2 respectively, are connected in series to supply mains. Then the effective electromotive force E, between mains, is the geometric sum of E_1 and E_2, as shown in Fig. 4. The angle ϕ depends upon the positions, relatively to the field magnets, of the armature coils on the respective machines, as is explained later.

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* NOTE. Alternating electromotive forces and alternating currents are added in the same way that forces are added, that is, by means of the principle known as the "parallelogram of forces."

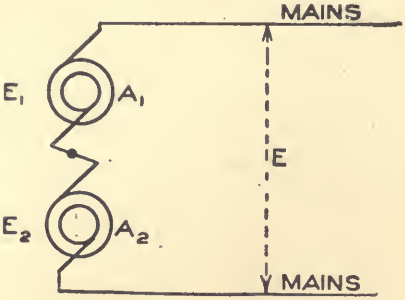


Fig. 3.

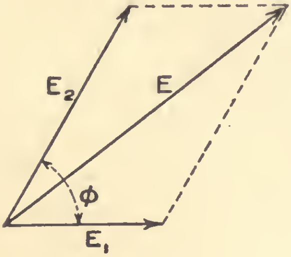


Fig. 4.

2b. When an alternating electromotive force E acts upon a number of elements or things in series, it is subdivided into parts, each of which acts upon one of the elements, and the "geometric" (or "vector") sum of these parts is equal to E.

Example. Two coils *b* and *c*, Fig. 5, are connected in series between mains supplied from an alternator, of which the effective electromotive force is E. Then the total effective electromotive force E is subdivided into two parts E_1 and E_2, which act upon the respective coils, as indicated in Fig. 5; and the "geometric" (or "vector") sum of E_1 and E_2 is equal to E, as shown in Fig. 6. The angles ϕ_1 and ϕ_2 depend upon the relative resistance and

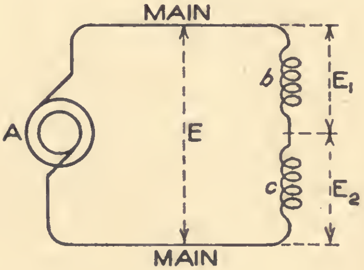


Fig. 5.

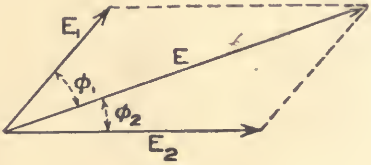


Fig. 6.

reactance of the respective coils. It is to be particularly noticed that the arithmetical sum of E_1 and E_2 is in general greater than E.

6. Physical Basis of Differences between Direct-Current Calculations and Alternating-Current Calculations. The abovementioned differences between direct-current and alternating-current calculations are due to the fact that an alternating current changes rapidly in value, while a direct current is steady. A clear idea of the effects of the rapid changes of an alternating current may be obtained as follows:

Fig. 7 represents an alternator producing alternating current in a circuit of wire; and Fig. 8 represents a valveless pump, of which the piston oscillates rapidly up and down, producing an alternating current of water in a circuit of pipe. The electromotive force of the alternator A not only has to overcome the resistance of the wire in order to cause an alternating current to surge back and forth through the circuit but it also has to overcome the electrical inertia of the circuit—first, in getting a pulse of current started; and then, in stopping this pulse of current and starting another in the reverse direction. The pressure developed by the pump P not only has to overcome the frictional resistance of the pipe in order to cause an alternating current of water to surge back and forth through the pipe, but it also has to overcome the inertia of the water in the pipe—first, in getting a pulse of water current started; and then, in stopping this pulse of water current and starting another in the reverse direction.

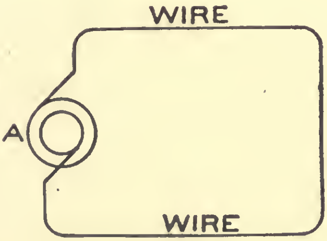


Fig. 7.

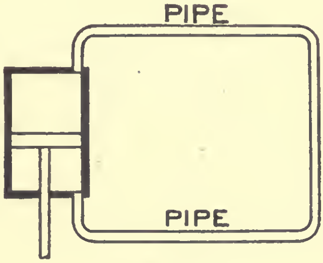


Fig. 8.

Fig. 9 represents an alternator producing alternating current in a circuit of wire which contains a condenser C; and Fig. 10 represents a valveless pump producing an alternating current of water in a circuit of pipe, which leads to a chamber H H, across which is stretched an elastic diaphragm D D. In this case the pressure developed by the pump has to overcome the frictional resistance of the pipe, the inertia of the water, and the elastic reaction of the diaphragm D D; and the alternating electromotive force of the alternator A, Fig. 9, has to overcome the electrical resistance of the wire, the electrical inertia of the wire circuit, and the electro-elastic reaction of the insulating material (or **dielectric**) between the plates of the condenser.

The electrical inertia of a circuit is called its **inductance**, and the electro-elasticity of a condenser is called its **capacity**. It is to these two things—inductance and capacity—that the peculiar features of alternating-current calculations are due.

The effect of capacity is strikingly shown by the fact that an alternating current may be made to flow through a circuit which for direct currents would be an open circuit like that shown in Fig 9. Thus an alternator connected to long transmission lines which are disconnected at the distant end and perfectly insulated from the ground, will send a perceptible alternating current into the lines, which can be measured by an alternating-current ammeter. In such a case the current is called the **charging current** of the line; and it may amount to several amperes, according to the length of the line, the distance apart and size of wires, and the electromotive force of the alternator.

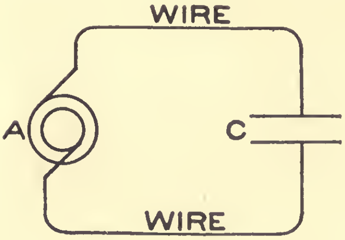


Fig. 9.

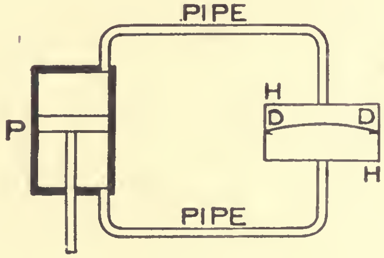


Fig. 10.

7. Graphical Representation of Alternating Electromotive Forces and Currents. When an armature conductor of an alternator approaches a *north* pole of the field magnet, the electromotive force of the machine rises in value as the conductor enters the strong field under the pole; and the electromotive force falls in value as the conductor passes from under the pole. As the conductor passes the point midway between two adjacent poles, the electromotive force of the machine falls to zero (since no lines of the force are cut at this point). As the armature continues to revolve and the conductor approaches the next (the *south*) pole of the field magnet, the electromotive force of the machine again increases in value, but in a direction opposite to that of the previous electromotive force; and it falls again to zero as the conductor passes from under the south pole and reaches the point midway between the next pair of poles.

Examples. In Fig. 11 are represented three successive poles S N S of the field magnet of an alternator, from which the lines of magnetic flux are emanating, and spreading out more or less as they enter the armature core. The armature core is shown as having only one slot A, which contains a number of armature conductors. The ordinates of the curve E E E E E E represent the successive instantaneous values of the electromotive force induced in the armature conductors as the slot moves from left to right.

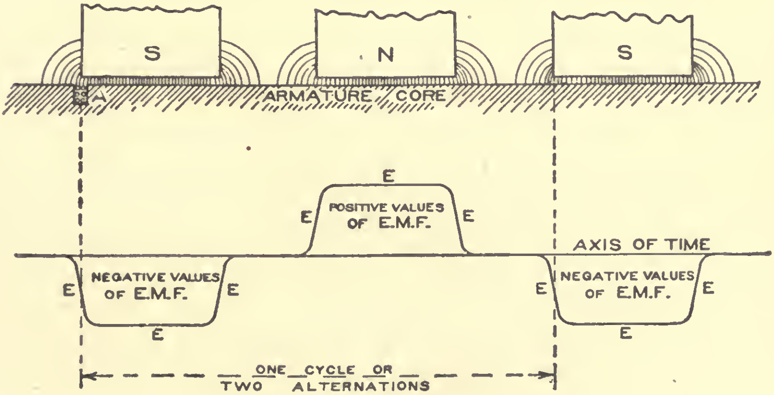

S
N
S
A
ARMATURE CORE
E
POSITIVE VALUES OF E.M.F.
E
E
AXIS OF TIME
E
NEGATIVE VALUES OF E.M.F.
E
E
E
NEGATIVE VALUES OF E.M.F.
E
E
ONE CYCLE OR TWO ALTERNATIONS

Fig. 11.

The duration of one cycle is indicated in the figure, and this cycle repeats itself as the conductors pass by successive *pairs* of field poles. Thus, in a ten-pole alternator, there would be five complete cycles, or five complete waves of the electromotive curve for each revolution.

The curve E E E E E E is called the **electromotive curve** or **electromotive force wave** of the alternator

A curve of which the ordinates represent the successive instantaneous values of the alternating current, is called an **alternating-current curve** or **alternating-current wave.**

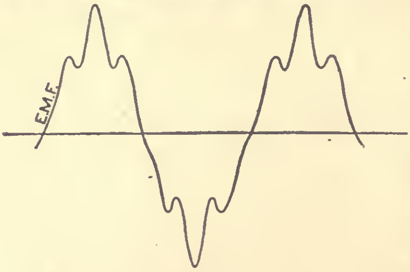


Fig. 12.

Figs. 12, 13 and 14 show typical forms of electromotive force curves given by commercial alternators. The exact shape of the electromotive force wave of an alternator depends upon the relations between pole pitch (distance from center to center of adjacent poles), width and shape of pole faces, width of armature coils, and distribution of coils on the armature.

8. Average Values and Effective Values. The average value of an alternating electromotive force or current *during a complete cycle* is zero, inasmuch as similar sets of positive and negative values occur. The average value of an electromotive force or current *during the positive (or negative) part of a cycle* is usually spoken of briefly as the "average value" or "mean value," and is not zero.

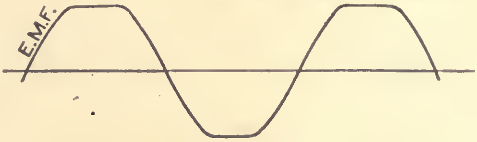


Fig. 13.

Consider now an alternating current, of which the instantaneous value is i. The rate at which heat is generated in a circuit through which the current flows is Ri^2, where R is the resistance of the circuit; and the *average* rate at which heat is generated in the circuit is R multiplied by the *average* value of i^2.

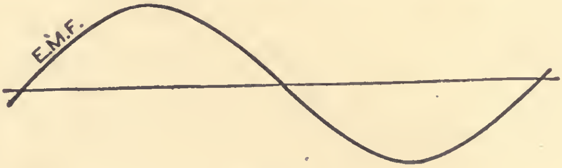


Fig. 14.

A continuous current which would produce the same heating effect would be one of which the square is equal to the average value of i^2, or of which the actual value is equal to $\sqrt{\text{average } i^2}$. This square root of the average square of an alternating current is called the **effective value** of the alternating current. Similarly, the square root of the average square of an alternating electromotive force is called the **effective value** of the alternating electromotive force

Ammeters and voltmeters used for measuring alternating electromotive force always give effective values irrespective of wave form; and in specifying an alternating electromotive force or current, its effective value is always used.

Example. Ten successive instantaneous values of an alternating electromotive force during half a cycle, are 0, 30, 60, 80, 90, 95, 90, 80, 60, and 30 volts. The sum of these values is 615 volts, which, divided by the number of values, namely ten, gives 61.5 volts, which is the average value of this electromotive force during half a cycle.

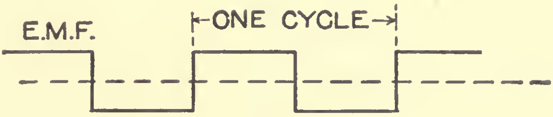


Fig. 15.

Squaring each of the above values, adding the squares together, and dividing their sum by their number, namely ten, gives the average value of the square of the electromotive force, which is 4,702.5 volts^2; and the square root of this average square is 68.6 volts, which is the effective value of the given electromotive force.

Form Factor. The ratio *effective value ÷ average value* depends upon the shape of the electromotive force wave, and is called the "form factor" of the wave.

Example. The form factor in the above case is $\frac{68.6}{61.5}$, or 1.12. The form factor of the electromotive force curve given in Fig. 14 is 1.11. The more peaked the wave the greater the value of its form factor. The rectangular electromotive force shown in Fig. 15 has a form factor equal to unity, which is the least possible value of the form factor. This rectangular wave, however, is never realized in commercial alternators.

9. Instantaneous and Average Power Delivered by an Alternator. Let e be the value, at a given instant, of the electromotive force of an alternator; and i the value of the current at the same instant. Then ei is the power in watts which is delivered by the alternator at the given instant; and the average value of ei is the average power delivered by the alternator.

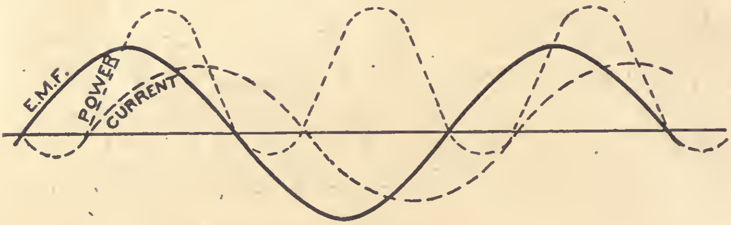


Fig. 16.

Examples. In Fig. 16 the full-line curve represents the electromotive force of an alternator; and the heavy-dotted curve the current delivered by the alternator to a receiving circuit having inductance. The ordinates of the light-dotted curve represent the successive instantaneous values of the power ei. As shown in the figure, the power has both positive and negative values; the

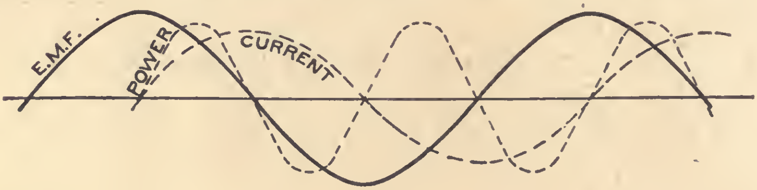
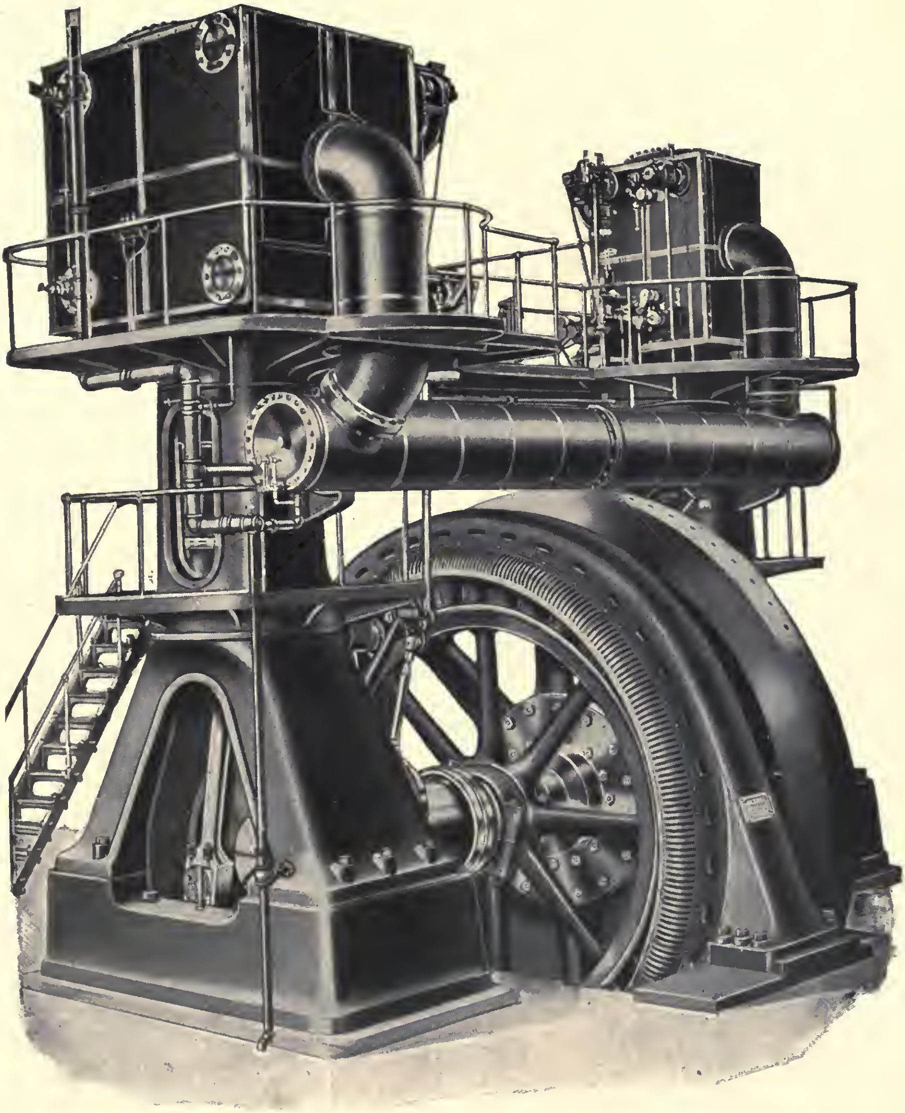


Fig. 17.

alternator does work on the circuit when ei is positive, and the circuit returns power to the alternator when ei is negative; and, of course, while ei is negative, the dynamo is momentarily a motor, and may for the moment return power to the fly wheel of the engine.

When the inductance of the receiving circuit is very large, the electromotive force and current curves are related as shown in Fig. 17; the instantaneous power ei passes through approximately



2,250-H.P. HAMILTON-CORLISS CROSS-COMPOUND CONDENSING ENGINE
AND 1,500-K.W. 3-PHASE, 6,600-VOLT NATIONAL ALTERNATOR.

similar sets of positive and negative values, as shown by the light-dotted curve; and the average power is approximately zero.

10. Definition of Harmonic Electromotive Forces and Currents. A line OP, Fig. 18, revolves at a uniform rate, f revolutions per second, about a point O, in the direction of the arrow gh. Consider the projection Ob of this rotating line upon the fixed line AB, this projection being considered positive when above O and negative when below O. A **harmonic electromotive force (or current)** is an electromotive force (or current) which is *at each instant proportional to the line Ob*. The line Ob represents at each instant the actual value e of the harmonic electromotive force to a definite scale, and the length of the line OP (which is the maximum length of Ob) represents the maximum value **E** of the harmonic electromotive force to the same scale. The line Ob passes through a complete cycle of values during one revolution of OP, and so also does the harmonic electromotive force e. Therefore the revolutions per second (f) of the line OP is the frequency of the harmonic electromotive force e. The rotating lines E and I, Fig. 19, of which the projections on a fixed line (not shown in the figure) represent the actual instantaneous values e and i of a harmonic electromotive force and a harmonic current, are said to "represent" the harmonic electromotive force and current respectively. Of course, the rotation of the lines E and I is a thing merely to be imagined. The rotation is understood to be in a counter-clockwise direction, as indicated in Fig. 18.

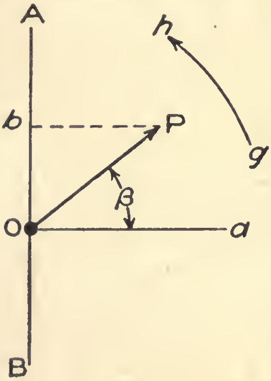


Fig. 18.

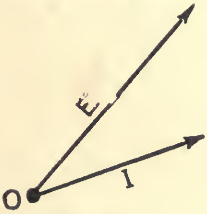


Fig. 19.

A diagram in which a number of electromotive forces or currents, or both, are represented by lines imagined to be revolving, is called a **clock diagram.** Simple problems involving relations between a number of *harmonic* electromotive forces and currents of the *same frequency*, are most easily treated by means of the clock diagram. When an electromotive force (or current) wave is not a sine curve, the electromotive force (or current) is not harmonic, and cannot properly be represented by a line in a clock diagram, because the projection of the rotating line is not at each instant proportional to the electromotive force (or current). The *approximate* representation, by lines in a clock diagram, of non-harmonic electromotive forces (or currents)—such, for example, as those represented by the curves in Figs. 12, 13, and 15, depends upon the finding of harmonic electromotive forces (or currents) which for the particular purpose in view are approximately equivalent to the actual given electromotive forces (or currents).

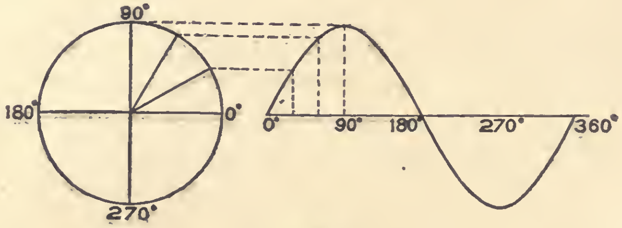


Fig. 20*a*.

A harmonic electromotive force or current is represented by a sine wave as shown in Fig. 14. The relation between the rotating line OP in Fig. 18 and the sine-wave curve of electromotive force, is shown as follows:

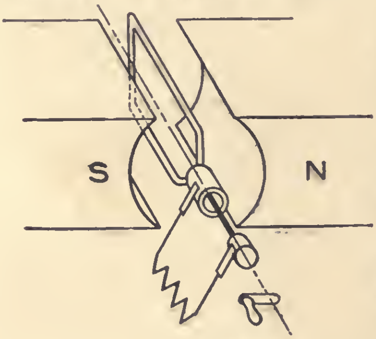


Fig. 20*b*.

Divide the circumference of the circle in Fig. 20*a* into equal parts, and lay off a horizontal line divided into the same number of equal parts.

Draw horizontal dotted lines through each division on the circumference of the circle, and vertical dotted lines through the corresponding divisions on the horizontal line. The points of the intersection of these pairs of dotted lines are points on a curve which is a curve of sines.

Example of Harmonic Electromotive Force. A flat loop of wire with its terminals connected to two collecting rings, gives a harmonic electromotive force when it is rotated at constant speed in a uniform magnetic field. This arrangement is shown in Fig. 20*b*.

11. Algebraic Expression of Harmonic Electromotive Force and Current. The line OP, Fig. 18, revolves uniformly f revolutions per second, and therefore it turns through $2\pi f$ radians * per second, since there are 2π radians in a revolution; that is,

$$\omega = 2\pi f, \qquad (8)$$

in which ω is the angular velocity of the line OP in radians per second. Let time be reckoned from the instant that OP coincides with O*a;* then, after t seconds, OP will have turned through the angle β $(=\omega t)$*;* and from Fig. 18 we have

$$Ob = \text{OP} \sin\beta = \text{OP} \sin\omega t,$$

since O*b* is the projection of OP on the line AB. But O*b* represents the actual value e of the harmonic electromotive force at the time t, and OP represents its maximum value E; therefore

$$e = \text{E} \sin\omega t \qquad (9)$$

is an algebraic expression for the actual value e of a harmonic electromotive force at time t, E being the maximum value of e, and $\frac{\omega}{2\pi}$ being the frequency according to equation 8.

Similarly, $$i = \text{I} \sin\omega t \qquad (10)$$

is an algebraic expression for the actual value i of a harmonic current at time t, I being the maximum value of i.

If time is reckoned from the instant that OP, Fig. 18, coincides with the line O*b*, then equations 9 and 10 become

$$e = \text{E} \cos\omega t.$$
$$i = \text{I} \cos\omega t.$$

12. Synchronism.—Phase Difference. Two alternating electromotive forces or currents are said to be in synchronism when they have the same frequency and are in phase. Two alternators are said to run in synchronism when their electromotive forces are in synchronism.

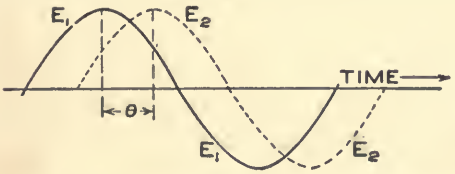


Fig. 21.

Consider two harmonic electromotive forces represented by the ordinates of the curves E_1 and E_2, Fig. 21. The electromotive force represented by the curve E_1 reaches its maximum value *before* the electromotive force represented by the curve E_2. The electromotive force E_1 is said to *lead* or *be ahead of* the electromotive force E_2 in *phase*. Conversely, the electromotive force E_2 is said to *lag behind* or to *follow* the electromotive force E_1 in *phase*. The same two electromotive forces E_1 and E_2 are also represented by the lines O E_1 and O E_2 in the clock diagram, Fig. 22. Here the line O E_2 is behind O E_1, since the imagined rotation is counter-clockwise. The **phase difference** is the time interval θ in Fig. 21, or the angle θ between O E_1 and O E_2 in Fig. 22.

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* NOTE. The unit of angle chiefly used in mechanics and in all theoretical work is the **radian.** It is the angle of which the arc is numerically equal to the radius (of a circle). There are, therefore, 2π radians in one circumference.

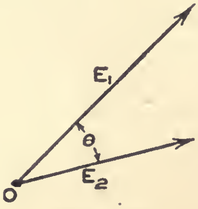

Fig. 22.

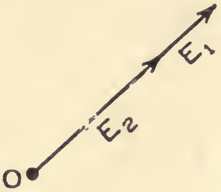

Fig. 23.

When the angle θ, Fig. 22, is zero, as shown in Fig. 23, the electromotive forces E_1 and E_2 are said to be **in phase.** In this case the electromotive forces increase together and decrease together; that is, when E_1 is zero, E_2 is also zero; and when E_1 is at its maximum value, so also is E_2, etc.

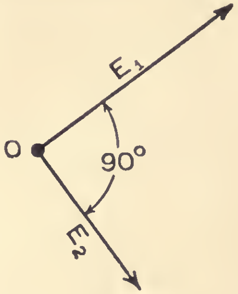

Fig. 24.

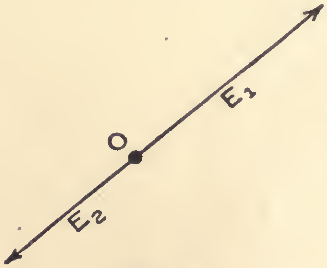

Fig. 25.

When $\theta = 90°$, as shown in Fig. 24, the two electromotive forces are said to be **in quadrature.** In this case one electromotive force is zero when the other is a maximum, etc.

When $\theta = 180°$, as shown in Fig. 25, the two electromotive forces are said to be **in opposition.** In this case they are at each instant opposite in sign; and when one is at its positive maximum, the other is at its negative maximum, etc.

13. Addition and Subtraction of Harmonic Electromotive Forces and Currents.—ADDITION. Consider two synchronous harmonic electromotive forces of which the successive instantaneous values e_1 and e_2 are represented by the projections of the lines E_1 and E_2, Fig. 26, which are imagined to be revolving about the point O. These electromotive forces being of the same frequency, the lines E_1 and E_2 revolve at the same speed, so that the angle between E_1 and E_2 remains unchanged in value. The ordinary arithmetical sum of e_1 and e_2, namely $e_1 + e_2$, is a harmonic electromotive force of the same frequency as e_1 and e_2; and this electromotive force $(e_1 + e_2)$ is represented by the projection of the line E, Fig. 26, which revolves at the same speed as E_1 and E_2.

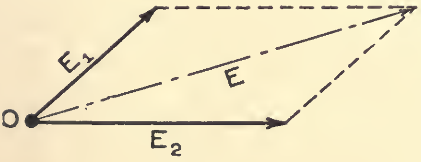

Fig. 26.

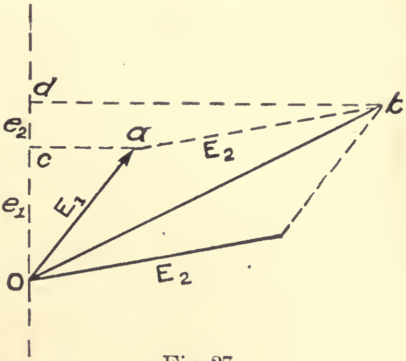

Fig. 27.

This is evident when we consider that the projection, on any line, of the diagonal of a parallelogram is equal to the sum of the projections of two adjacent sides of the parallelogram, as shown in Fig. 27. The projection of E_1 is O*c*, which represents e_1; and the projection of E_2 is equal to *cd*, which represents e_2. The projection of the diagonal O*b* of the parallelogram is O*d*, which is the sum of O*c* and *cd*. The two lines marked E_2 in Fig. 27 are equal and parallel, and have therefore the same projected length on the vertical line.

Corollary. The ordinary arithmetical sum $(e_1 + e_2 + e_3 +$ etc.), of the instantaneous values of any number of synchronous electromotive forces (or currents), is another harmonic electromotive force (or current) of the same frequency; and it is represented in magnitude and phase by a line that is the geometric (or vector) sum of the lines representing the given individual electromotive forces (or currents). This is evident when we consider that $e_1 + e_2$ is a harmonic electromotive force (or current) according to the above discussion; and this, added to e_3, gives an electromotive force (or current) which is harmonic and of the same frequency as e_1, e_2, and e_3.

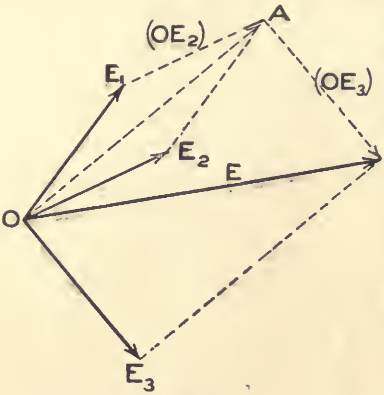

Fig. 28.

The **geometric** or **vector sum** of a number of lines is defined as follows: Given three lines O E_1, O E_2, and O E_3, Fig. 28. Find the diagonal O A of the parallelogram constructed on O E_1 and O E_2 as sides. This gives the vector sum of O E_1 and O E_2. Next construct a parallelogram on O A and O E_3 as sides; the diagonal O E of this parallelogram is the vector sum of the three given lines. This line O E is the closing side of the polygon formed by drawing O E_1, then drawing (O E_2) from the extremity of O E_1 (this giving the point A), and then drawing (O E_3) from A. This method is called *addition by means of the vector polygon.*

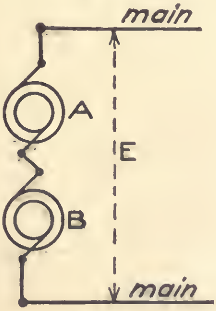

Fig. 29.

SUBTRACTION. One harmonic electromotive force (or current) is subtracted from another by reversing the direction of the line that represents it in the clock diagram, and then *adding* the reversed line (or vector) to the other. An example of the subtraction of harmonic electromotive forces will be given in connection with the discussion of three-phase electromotive forces.

Examples of Addition of Harmonic Electromotive Forces and Currents.

1. Two alternators A and B running in synchronism are connected in series between mains as shown in Fig. 29. If the electromotive forces of A and B are in phase, the electromotive

force between the mains will be simply the numerical sum of the electromotive forces of A and B. If, on the other hand, the electromotive forces of A and B differ in phase, the state of affairs will be as represented in Fig. 30, in which the lines A and B represent the electromotive forces of the alternators A and B respectively, θ is the phase difference of A and B; and the line E represents the electromotive force between the mains.

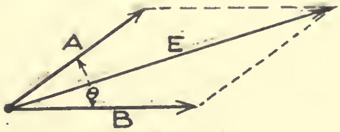

Fig. 30.

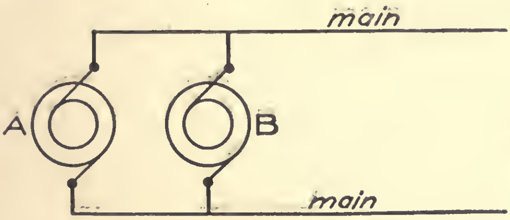

Fig. 31.

2. Two alternators A and B running in synchronism are connected in parallel between the mains as shown in Fig. 31. Let the lines A and B, Fig. 32, represent the currents given by the alternators A and B respectively, the phase difference being θ; then the current in the main line is represented by I.

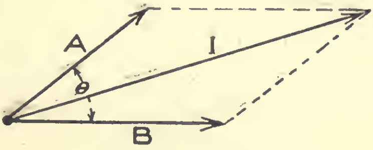

Fig. 32.

3. Two circuits A and B are connected in series between the mains of an alternator as shown in Fig. 33. The line E, Fig. 34, represents the electromotive force between the mains; the line A represents the electromotive force between the terminals of the circuit A; and the line B represents the electromotive force between the terminals of the circuit B. The circuits A and B are supposed to have inductance. If one of the circuits, A or B, contains a condenser, then the electromotive forces A and B, Fig. 34, may be nearly opposite to each other in phase, and A and B may each be indefinitely greater than the electromotive force E between the mains.

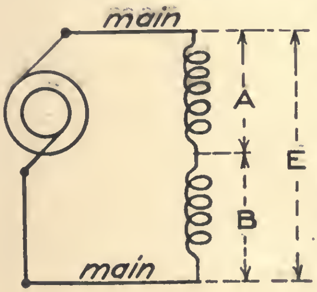

Fig. 33.

4. Two circuits A and B, Fig 35, are connected in parallel across the terminals of an alternator as

shown. The current I from the alternator is related to the currents A and B as shown in Fig. 36. If one of the circuits, A or B, contains a condenser, then the currents A and B may be nearly opposite to each other in phase, and the currents A and B may each be indefinitely greater than the current I from the alternator.

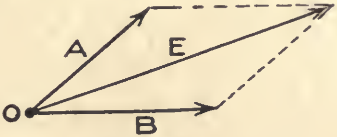

Fig. 34.

14. Relation between Maximum and Effective Values of Harmonic Electromotive Forces and Currents. The effective value E or I of a harmonic (that is, a sine-wave) electromotive force (or current), is equal to the maximum value **E** or **I** divided by the square root of 2. That is,

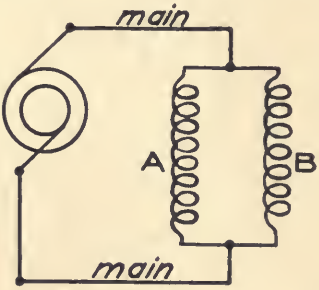

Fig. 35.

$$E = \frac{\mathbf{E}}{\sqrt{2}}. \qquad (11)$$

$$I = \frac{\mathbf{I}}{\sqrt{2}}. \qquad (12)$$

PROOF. Let e ($= \mathbf{E} \sin \omega t$) be a harmonic electromotive force. To find the average value of e^2 ($= \mathbf{E}^2 \sin^2 \omega t$), it is necessary to find the average value of the square of the sine of the uniformly variable angle ωt. We have the general relation,

$$\sin^2 \omega t + \cos^2 \omega t = 1, \qquad (a)$$

so that

$$\text{Av.} \sin^2 \omega t + \text{Av.} \cos^2 \omega t = 1. \qquad (b)$$

Now, during a cycle, the cosine of a uniformly variable angle passes similarly through the same set of values as the sine; hence Av. $\sin^2 \omega t$ and Av. $\cos^2 \omega t$ are equal, so that from equation b, above, we have:

$$2 \text{ Av.} \sin^2 \omega t = 1;$$

or,

$$\text{Av.} \sin^2 \omega t = \tfrac{1}{2}.$$

The average value of e^2 is

$$\text{Av.} e^2 = \mathbf{E}^2 \text{ Av.} \sin^2 \omega t;$$

or,

$$\text{Av.} e^2 = \frac{\mathbf{E}^2}{2},$$

and $$\sqrt{\text{Av.}\, e^2} = \frac{E}{\sqrt{2}}.$$

In Fig. 18 the length of the revolving line OP was understood to represent the **maximum value** of the harmonic electromotive force (or current). When, however, a number of harmonic electromotive forces (or currents) are represented to scale by lines in a clock diagram, the lengths of the lines may be interpreted as giving not maximum but **effective values**, since there is a constant ratio $\sqrt{2}$ between the effective and maximum values of each of the electromotive forces (or currents) represented in the diagram.

It is desirable to interpret the lines in a clock diagram in terms of effective values rather than maximum values, because effective values are always given by measuring instruments and are nearly always used in numerical calculation. Therefore, unless it is expressly stated to the contrary, the lines in clock diagrams are always understood to represent effective values.

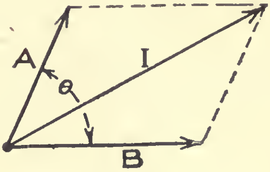

Fig. 36.

Examples. A certain harmonic alternating current gives a reading of 100 amperes on an alternating-current ammeter, and its effective value is therefore 100 amperes. This harmonic current actually pulsates between zero and a maximum value of $\pm \sqrt{2} \times$ 100 amperes, or $\pm$ 141.4 amperes.

A certain harmonic alternating electromotive force gives a reading of 1,000 volts on an alternating-current voltmeter, and its effective value is therefore 1,000 volts. This electromotive force actually varies between zero and a maximum value of $\pm \sqrt{2} \times$ 1,000 volts, or $\pm$ 1,414 volts.

This relation between maximum and effective values is true only for harmonic (that is, sine-wave) electromotive forces and currents. In general, the maximum values of alternating electromotive forces (or currents) cannot be inferred from effective values as measured by ammeters and voltmeters. Thus, an alternating electromotive force which is known to have a peaked-wave form might have a maximum value very greatly in excess of $\sqrt{2}$ times its effective value.

15. Expression for Power in Cases of Harmonic Electromotive Forces and Currents.

(*a*) When the current is in phase with the electromotive force, that is, when the circuit is non-inductive, then the power (average ei, see article 9) is

$$P = E\,I, \qquad (13)$$

in which P is the power in watts, E is the effective value of the electromotive force in volts, and I is the effective value of the current in amperes. Equation 13 is identical with the power equation for direct-current circuits.

(*b*) If the phase difference between current and electromotive force were 90°, which can never actually occur, then the power (average value of ei) would be equal to zero, as explained in article 9.

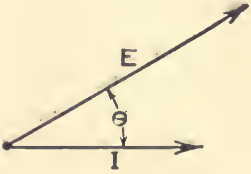

Fig. 37.

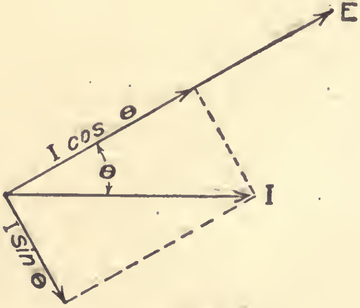

Fig. 38.

(*c*) When the phase difference between current and electromotive force is $\theta°$, as shown in Fig. 37, then

$$P = E\,I\cos\theta, \qquad (14)$$

in which P is the power (average ei) in watts, E is the effective value of the electromotive force in volts, and I is the effective value of the current in amperes.

Discussion of Case *c*. The given current I shown in Fig. 37 may be thought of as resolved into two components, as shown in Fig. 38. One of these components ($I\cos\theta$) is parallel to (that is, in phase with) E; and the other ($I\sin\theta$) is at right angles to E. The power corresponding to the actual current I may be thought of as the sum of the powers corresponding to its two components respectively. But the component $I\sin\theta$ is at right angles to E, as in case *b* above; hence the power corresponding to it is zero. This component is therefore frequently called the **wattless component** of the given current.

On the other hand, the component I cos θ is parallel to (that is, in phase with) E, as in case *a* above; hence the power corresponding to this component is equal to $E \times I \cos \theta$. The component I cos θ of the given current I is frequently called the **power component** of I; and the factor cos θ is called the **power factor** of the circuit.

16. Inductance. It has been pointed out in article 6 that an electric circuit has a certain kind of inertia analogous to the inertia of water in a circuit of pipe, and it was there noted that this inertia of an electric circuit is called inductance. If an electric current in a circuit is made to change in value, a portion of the electromotive force acting upon the circuit must be used to *cause* the current to change.

In the same way a force, over and above that required to overcome frictional resistance, must act upon a moving body to accelerate it, that is, to make its speed increase. The inertia of a body is measured by the force required to accelerate it at the rate of unit change in speed per second; and the inductance of a circuit is measured by the electromotive force required to cause a current in the circuit to change at the rate of one ampere per second. A circuit is said to have an inductance of one **henry*** when one volt (over and above the electromotive force required to overcome the electrical resistance) will cause the current to change at the rate of one ampere per second.

Let x be the rate in amperes per second at which the current in a circuit is increasing in value. Then the electromotive force E (over and above that required to overcome the resistance of the circuit) required to cause the current to increase at this rate is:

$$E = L\,x, \qquad \textbf{(15a)}$$

in which L is the inductance of the circuit in henrys, E being expressed in volts.

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* NOTE. The henry is a very large inductance, and the inductances usually met with in practice are expressed in thousandths of a henry, that is, in milli-henrys.

Example. The coil of a large electro-magnet has 2.5 henrys of inductance and 5 ohms of resistance. At a given instant this coil is connected to 110-volt direct-current mains. At the instant of connecting the coil, the current is zero, and all of the 110 volts is used to cause the current in the coil to increase, so that, according to equation 15a, x is equal to E/L, or 110 volts ÷ 2.5 henrys, or 44 amperes per second. That is, the current in the magnet coil begins to increase at the rate of 44 amperes per second. When the current in the magnet coil has reached the value of 10 amperes, 50 volts (=5 ohms × 10 amperes) of the total 110 volts are used in overcoming the resistance of the coil, so that 60 volts (= 110 volts — 50 volts) are used to make the current increase. Therefore, as the current in the coil passes the value of 10 amperes, it is increasing at the rate E/L = 60 volts ÷ 2.5 henrys = 24 amperes per second.

The inductance of a coil wound on a given spool is proportional to the square of the number of turns N of wire. For example, a given spool wound with No. 16 wire has 500 turns and an inductance of, say, 0.025 henry; the same spool wound with No. 28 wire would have about ten times as many turns, and its inductance would be about 100 times as great, or 2.5 henrys.

The inductance of a coil of given shape is proportional to its linear dimensions, the number of turns of wire being unchanged. For example, a given coil has an inductance of 0.022 henry; and a coil three times as large in length, diameter, etc., but having the same number of turns of wire, has an inductance of 0.066 henry.

Formulæ for Calculating Inductance. The inductance in henrys of a coil of wire wound in a thin layer on a long wooden cylinder of length l centimeters and of radius r centimeters, is:

$$L = \frac{4\,\pi^2\,r^2\,N^2}{l \times 10^9}, \qquad \text{(15b)}$$

in which N is the total number of turns of wire in the coil. This equation is strictly true for very long coils wound in a thin layer; but the equation is very useful, also, in calculating the approximate inductance of even short, thick coils. Thus a coil 25 centimeters long and $2\frac{1}{2}$ centimeters mean radius, containing 150 turns of wire, has an approximate inductance of

$$L = \frac{4\,\pi^2\,(2.5)^2 \times 150^2}{25 \times 10^9} = 0.00022 \text{ henry.}$$

If a coil of N turns of wire is wound on a long rod of iron, instead of wood or other non-magnetic material, the inductance in henrys is given by the equation

$$L = \frac{4\,\pi^2\,r^2\,N^2\,\mu}{l \times 10^9}, \qquad (16)$$

in which L , r, N, and l are the same as in equation 15b, and μ is the permeability of the iron core at the particular flux-density produced in the iron. This equation applies to any iron rod of length l centimeters and radius r centimeters, wound with N turns of wire, whether in the form of a long, straight rod or bent into a closed ring.

The permeability μ of iron varies from 500 to 1,000 or more; and therefore the effect* of placing an iron core in a coil is greatly to increase the inductance of the coil.

The iron core of an inductance coil to be used with alternating currents should be laminated to reduce eddy currents and consequent loss of energy, and to prevent excessive heating of the core.

Examples. The inductance of the field coil of a certain shunt-wound dynamo is 7.5 henrys.

The inductance of a pair of No. 0, B. & S. copper line wires carried at a distance of 18 inches apart on a pole line, is 0.0035 henry per mile.

The inductance of the secondary coil of a large induction coil (X-ray coil) having 200,000 turns of wire, is 2,000 henrys.

Inductances in Series and in Parallel. The inductance of two or more coils *in series* is equal to the sum of the individual inductances.

The equivalent inductance of two or more similar coils *in parallel*, such as the similar coils on an armature, is equal to $1/n$ of the inductance of one coil, n being the number of coils connected in parallel.

---

* NOTE The permeability μ of a given sample of iron is not constant, but decreases in value as the magnetizing force increases. Therefore the inductance L of a coil having an iron core, is not a definite constant quantity as is the inductance of a coil without an iron core.

17. Capacity. It has been pointed out in article 6 that a charged condenser has an elastic-like reaction analogous to the elastic reaction of a distorted diaphragm. The elasticity of a diaphragm might be measured by the pressure required to distort it to the extent of producing one unit of increase of volume in the space on one side of the diaphragm, and one unit of decrease of volume in the space on the other side of the diaphragm. Similarly, the capacity of a condenser may be, and in fact is, measured by the electromotive force required to force one unit of charge of electricity into one plate of the condenser, and at the same time to withdraw one unit of charge from the other plate. A condenser is said to have a capacity of one **farad** when one volt of electromotive force pushes one coulomb of electric charge into the condenser.*

The charge Q pushed into a condenser by a steady electromotive force E is,

$$Q = C E, \qquad \textbf{(17a)}$$

in which C is the capacity of the condenser in farads, Q is the charge in coulombs, and E is the electromotive force in volts. The electromotive force required to hold a given charge Q in the condenser is of course equal to Q/C.

Condensers, to have a large capacity (as much as a microfarad), are usually made up of alternate sheets of tinfoil and waxed paper or mica, as indicated in Fig. 39. Alternate metal sheets are connected together as shown, thus practically forming two plates of large area.

Fig. 39.

Inductivity of Dielectric. The material between the plates of a condenser is called a **dielectric.** The capacity of a condenser of given dimensions depends upon the material used as the dielectric. The quotient *capacity of a condenser with given dielectric ÷ its capacity with air as the dielectric* is called the **inductivity** of the given dielectric.

---

* Note. The farad is an exceedingly large capacity, and capacities encountered in practice are usually expressed in millionths of a farad, that is, in microfarads.

TABLE II.

Inductivities.

Air equal to unity.

Glass	3.00 to 10.00	Mica	4.00 to 8.00
Vulcanite	2.50	Shellac	2.95 to 3.60
Paraffin	1.68 to 2.30	Turpentine	2.15 to 2.43
Beeswax	1.86	Petroleum	2.04 to 2.42

Formula for Calculating the Capacity of a Condenser. The capacity of a condenser is given by the equation,

$$C_{\text{farads}} = 885 \times 10^{-16} \times \frac{ka}{x}, \qquad \textbf{(17b)}$$

in which a is the combined area in square centimeters of all the leaves of dielectric between the condenser plates, x is the thickness in centimeters of the dielectric leaves, and k is the inductivity of the dielectric used.

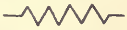
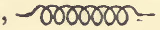
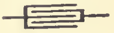
Examples. The capacity of an ordinary 2-quart Leyden jar is about 0.005 microfarad. The capacity of an average submarine telegraph cable is about 0.4 microfarad per nautical mile. The capacity of a pair of transmission lines of No. 0, B. & S. wires placed 18 inches apart between centers on poles, is 0.036 microfarad per mile.

Capacities in Series and in Parallel. The capacity of a number of condensers *in parallel* is equal to the sum of the individual capacities.

The capacity of a number of condensers *in series* is,

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \text{etc.}}, \qquad \textbf{(18)}$$

in which C_1, C_2, C_3, etc., are the individual capacities, and C is the joint capacity.

18. The Fundamental Equation of the Alternating-Current Circuit. An alternator A, Fig. 40, delivers an alternating current of I amperes, effective, to a circuit consisting of a resistance of R ohms, an inductance of L henrys, and a condenser of which the capacity is C farads, all connected in series. It is to be remembered that any coil having inductance has resistance also; that is, inductance and resistance are inseparable. Nevertheless inductance and resistance are essentially different in nature and in their effects, and they are always considered separately, so that it is helpful to think of them as actually separated in a circuit, as indicated in Fig. 40. A resistance is conventionally represented thus, ; an inductance thus, ; and a condenser thus, .

The current in the circuit, Fig. 40, is assumed to be harmonic, that is, to be a sine-wave current, and this current is represented by the line O I in Fig. 41.

A portion of the electromotive force of the alternator is used to overcome the resistance of the circuit. The portion of the electromotive force so used is an alternating electromotive force of which the effective value is RI; it is in phase with the current, and is represented by the line RI in Fig. 41.

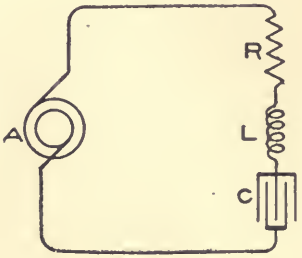


Fig. 40.

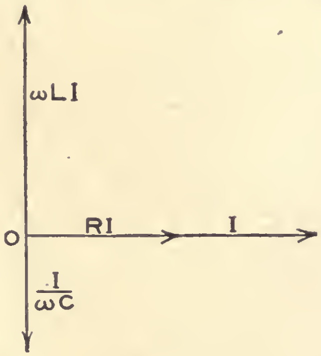
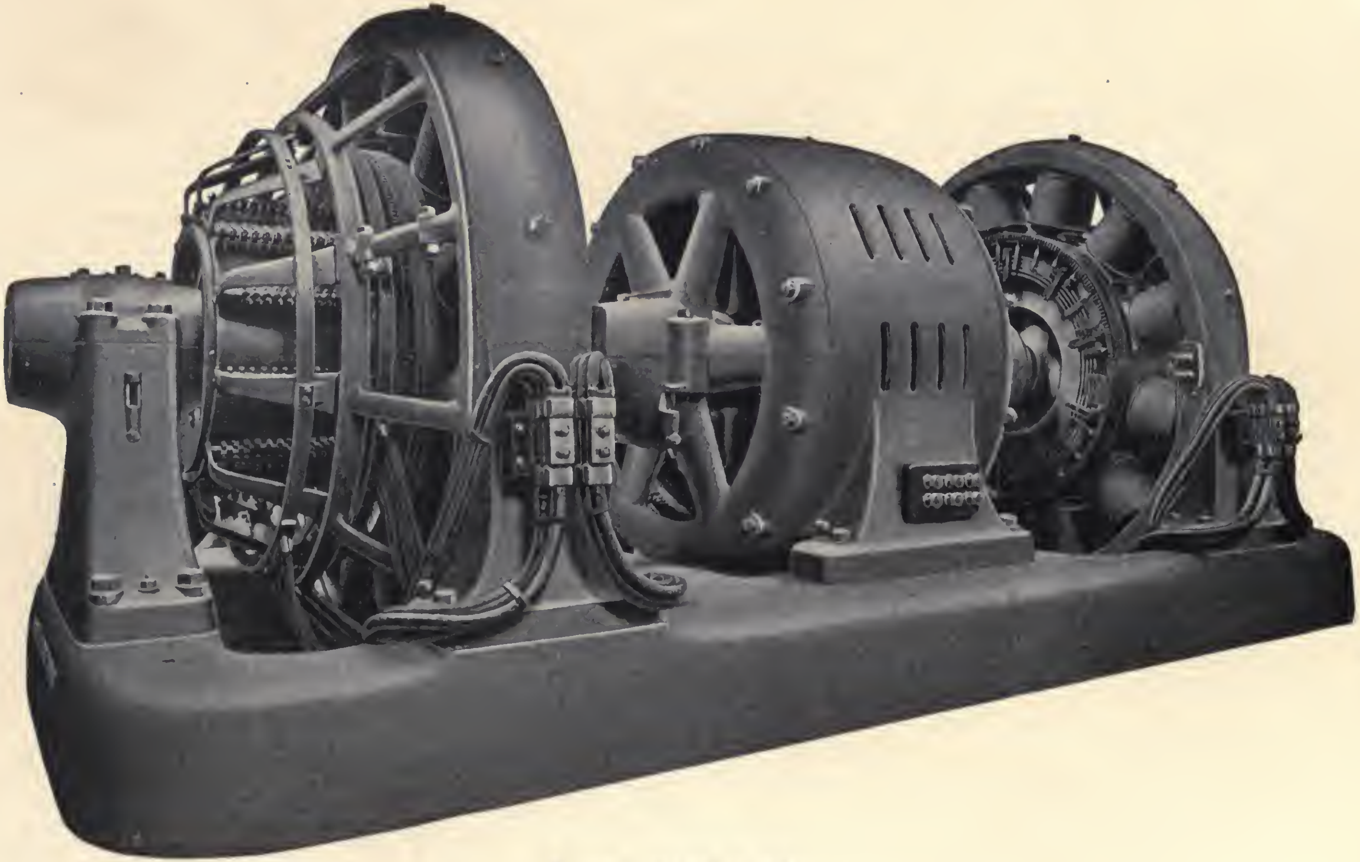


Fig. 41.

A portion of the electromotive force of the alternator is used to overcome the inertia or inductance of the circuit in causing the current to increase and decrease. The portion of the electromotive force so used is an alternating electromotive force of which the effective value is ωLI; it is 90° ahead of I in phase, and is represented by the line ωLI in Fig. 41. The quantity ω is equal to 2π times the frequency of the current I.

A portion of the electromotive force of the alternator is used to overcome what we have previously called the electro-elasticity of the condenser, or, in other words, to hold electric charge on the



MOTOR GENERATOR SET.
1.200 H.P. Induction Motor, Direct-Connected to 400 K.W. D.C. Generator.
General Electric Co.

condenser plates at each instant. The portion of the electromotive force so used is an alternating electromotive force of which the effective value is $\frac{I}{\omega C}$; it is 90° behind I in phase, and is represented by the line $\frac{I}{\omega C}$ in Fig. 41.

The total electromotive force E of the alternator is equal to the geometric (or vector) sum of the parts RI, ωLI, and I / ωC. This vector sum is formed by subtracting I / ωC from ωLI, since it is opposite to ωLI in direction, and then adding RI and (ωLI — I / ωC) geometrically, as shown in Fig. 42, in which the line O*a* represents $(\omega LI - \frac{I}{\omega C})$, and the line E represents the geometric sum of O*a* and RI.

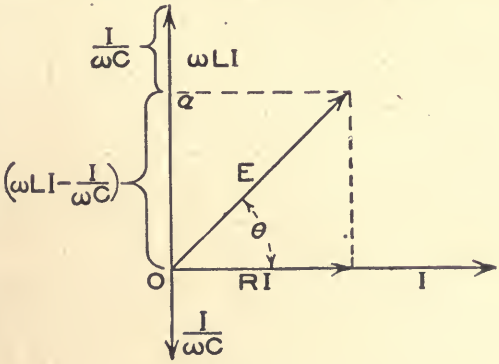


Fig. 42.

From Fig. 42 we have, by geometry:

$$E^2 = R^2 I^2 + (\omega L I - \frac{I}{\omega C})^2;$$

or,
$$E^2 = I^2 \left[R^2 + (\omega L - \frac{1}{\omega C})^2 \right];$$

or,
$$I = \frac{E}{\sqrt{R^2 + (\omega L - \frac{1}{\omega C})^2}}. \qquad (19)$$

The quantity $\omega L - \frac{1}{\omega C}$ is called the **reactance** of the circuit The term ωL is often called **inductance reactance;** and the term $\frac{1}{\omega C}$ is often called **capacity reactance.** Inductance reactance is always positive, and capacity reactance is always negative. It is convenient to represent the reactance $\omega L - \frac{1}{\omega C}$ of a circuit by the single letter X; that is

$$X = \omega L - \frac{1}{\omega C}. \qquad (20)$$

Therefore, writing X for $\omega L - \frac{1}{\omega C}$ in equation 19, we have:

$$I = \frac{E}{\sqrt{R^2 + X^2}}. \qquad (21)$$

Furthermore, from the right triangle in Fig. 42, we have:

$$\tan \theta = \frac{\omega L - \frac{1}{\omega C}}{R};$$

or,

$$\tan \theta = \frac{X}{R}, \qquad (22)$$

in which θ is the angle of phase lag of the current I behind the electromotive force E, X is the reactance of the circuit, and R is the resistance of the circuit.

19. Resistance, Reactance, and Impedance. Consider a harmonic alternating electromotive force E which produces a harmonic alternating current I in a circuit. This electromotive force may be resolved into two components, one parallel and the other perpendicular to I, as shown, for example, in Fig. 41. The component of E parallel to I is equal to RI. The **resistance** of an alternating-current circuit is sometimes defined as that factor which, multiplied by the current, gives the component (of the electromotive force) which is parallel to I.

The component of E perpendicular to I is equal to $\omega LI - \frac{I}{\omega C}$, or to X I. The **reactance** of an alternating-current circuit may be defined as that factor which, multiplied by the current, gives the component (of the electromotive force) which is perpendicular to I.

The factor $\sqrt{R^2 + X^2}$, which, when multiplied by the current I, gives the total value of the electromotive force E, is called the **impedance** of the alternating-current circuit. Of course, E divided by the impedance gives the value of the current I.

Resistance, reactance, and impedance are all expressed in ohms; we may, for example, speak of 10 ohms of resistance, 10 ohms of reactance, or 10 ohms of impedance. Thus, ohms are used in alternating-current work to express the three essentially different things—resistance, reactance, and impedance; and a specification of a certain number of ohms is not intelligible unless it is stated whether it is ohms of resistance, ohms of reactance, or ohms of impedance.

The reactance and the impedance of a circuit depend upon the frequency of the alternating current, as well as upon the physical constants L and C of the circuit, since the factor ω is equal to 2π times the frequency.

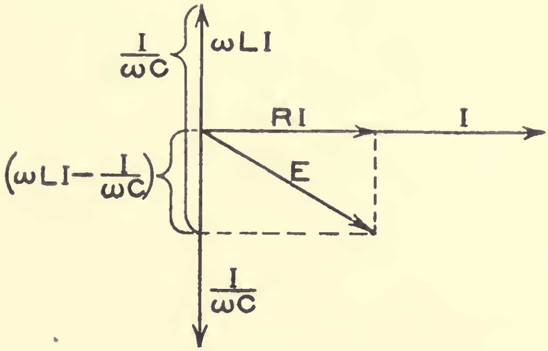


Fig. 43.

The reactance of a circuit may be positive or negative, according as ω L is larger than or less than $\frac{1}{\omega C}$. When reactance is positive, the inductance reactance ω L exceeds the capacity reactance $\frac{1}{\omega C}$, and the current is behind the electromotive force in phase, as shown in Fig. 42. When the reactance is negative, the capacity reactance exceeds the inductance reactance, and the current is ahead of the electromotive force in phase, as shown in Fig. 43.

20. Special Cases of Electromotive Force and Current Relations in Alternating-Current Circuits. A clear understand-ing of the following examples as special cases of the general relations of electromotive force and current as discussed in articles 18 and 19, depends upon the following facts:

1. That the effect of inductance in an alternating-current circuit becomes negligible when the inductance is very small, for then the reactance ωL due to the inductance is small, and the portion of the electromotive force required to overcome the inductance (namely, $\omega L I$, Fig. 41) is also small.

2. That the effect of a condenser in an alternating-current circuit becomes negligible only when the capacity of the condenser is very large, for then the reactance $-\frac{1}{\omega C}$ due to the condenser is small, and the portion of the electromotive force required to overcome the electro-elasticity of the condenser (namely, $\frac{1}{\omega C}$, Fig. 41), is also small.

The effect of an inductance may be rendered negligible by short-circuiting it with a low-resistance wire; and the effect of a condenser also may be rendered negligible by short-circuiting it with a low-resistance wire.

CASE A. *Non-inductive or Non-reactive Circuits.* A circuit which does not contain a condenser and does not have any perceptible inductance is called a **non-reactive** circuit. The term **non-inductive** is frequently used in the sense in which non-reactive is here defined. A non-reactive circuit contains only resistance; and the total electromotive force required to produce a given alternating current I in a non-reactive circuit of which the resistance is R ohms, is RI volts,* and the electromotive force and current are in phase with each other. Therefore the relation between alternating electromotive force and current in a non-reactive circuit is precisely the same as in the case of direct currents. That is,

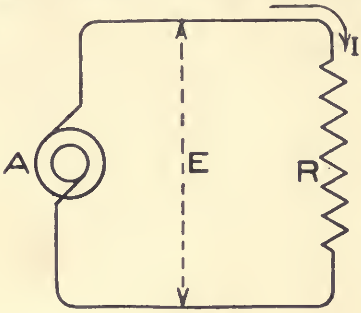


Fig. 44.

$$E = RI;$$

or,

$$I = \frac{E}{R}. \qquad (23)$$

Fig. 44 represents a non-reactive circuit connected to an alternator A; and Fig. 45 shows the relation between the electromotive force and current.

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* NOTE. Effective values are always understood except where it is distinctly stated to the contrary.

Example. Any circuit in which the outgoing and returning wires are very near together, has very small inductance. An ordinary incandescent lamp, for example, has a negligible inductance.

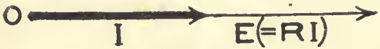


Fig. 45.

An incandescent lamp the resistance of which when hot is 220 ohms, takes half an ampere effective when connected to alternating-current supply mains between which the effective electromotive force is 110 volts; the current is in phase with the electromotive force, and the power in watts is equal to the product of effective volts times effective amperes, or 55 watts. Alternating-current voltmeters are always made as nearly as possible non-inductive.

Case B. *Circuits Containing Resistance and Inductance.* In this case the reactance X ($= \omega L$) is positive, and the current

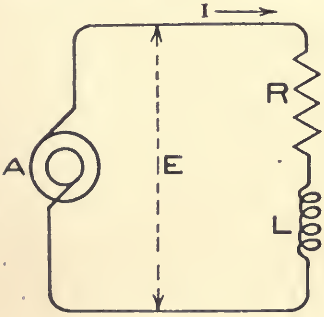


Fig. 46.

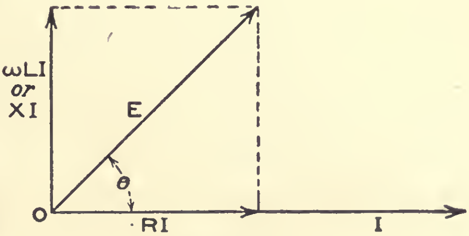


Fig. 47.

lags behind the electromotive force in phase, as before pointed out. The tangent of the angle of lag is equal to $\frac{X}{R}$, according to equation 22; therefore the angle of lag of the current is small when X is small compared with R, and the angle of lag approaches 90° when X is very large compared with R.

Fig. 46 represents a circuit containing resistance and inductance, connected to an alternator A; and Fig. 47 shows the relation between the electromotive force and current.

Example. A coil of wire usually has a very considerable inductance, especially if it is wound on a laminated iron core. In fact, a coil wound on a laminated iron core usually has so large a reactance, X ($= \omega$ L), that the angle θ, Fig. 47, is very nearly 90°. Thus, a certain coil has a resistance of 2 ohms and an inductance of 0.3 henry when provided with a laminated-iron core. This coil is connected to an alternator giving 1,000 volts effective electromotive force at a frequency of 133 cycles per second, so that the factor ω is equal to $2\pi \times 133$, or 835.7 radians per second; the reactance of the coil is 835.7×0.3, or 250.7 ohms; the impedance is $\sqrt{2^2 + 250.7^2}$, or 250.7 ohms; the current is $\frac{1{,}000}{250.7}$, or 3.989 amperes; the current lags about 89½° behind the electromotive force; and the power delivered to the coil is 1,000 volts × 3.989 amperes × cos 89½°, which is equal to 34.82 watts ($= \mathrm{R}\ \mathrm{I}^2$). The product EI, sometimes called **apparent watts**, is equal to 3,989 volt-amperes.

This example illustrates one remarkable feature of alternating currents—namely, the very small amount of actual power that is delivered to a circuit of large reactance even though the electromotive force is large and the current considerable. In the case of a direct current, 3.989 amperes taken from 1,000-volt mains would mean an actual delivery of 3,989 watts of power, while in the above case the actual power delivered is only 34.82 watts. The ratio *true watts ÷ apparent watts* is called the **power factor** of a circuit; and in case of the coil here under discussion, this ratio is equal to about 0.008 ($= \cos\theta$).

One never encounters in practice a circuit in which the reactance is so large compared to the resistance as in the above example; that is, he never encounters one in which the power factor is so small as 0.008. Cases are often met with, however, where the reactance is from two to ten times as large as the resistance. Thus, one of the primary windings of a certain 110-volt induction motor has a resistance of 0.7 ohm and a reactance of 4.2 ohms. When the motor is running at zero load this circuit, according to equation 21, takes $\frac{110}{\sqrt{0.7^2 + 4.2^2}} = \frac{110}{4.258}$, or 25.83 amperes; the angle of phase lag of the current, according to equation 22, is about 80½°; and the power factor of the circuit is 0.164.

A circuit which contains a coil wound on an iron core takes more power than is expended in the mere heating of the wire, namely RI^2, for some power is consumed in the iron core on account of magnetic hysteresis and eddy currents. In the above examples this consumption of power in an iron core is neglected for the sake of simplicity.

Case C. *Circuits Containing Resistance and a Condenser.* In this case the reactance X $(= -\frac{1}{\omega C})$ is negative, and the current leads the electromotive force in phase, as before pointed out. The tangent of the angle of lead is equal to $\frac{X}{R}$, according to equation 22; and therefore the angle of lead of the current is small when X is small compared with R (that is, when ωC is large), while the angle of lead of the current approaches 90° when X is large compared with R (that is, when ωC is small).

Fig. 48 represents a circuit containing resistance and a condenser, connected to an alternator A; and Fig. 49 shows the relation between the electromotive force and current.

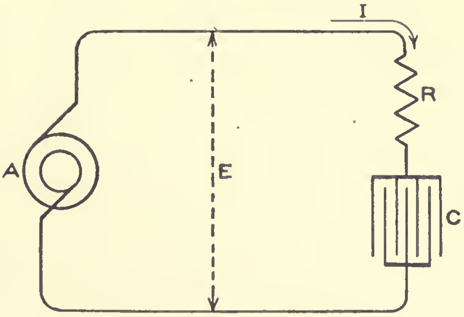


Fig. 48.

Example. A condenser with a capacity of 2 microfarads (which is large, as condensers go) is connected to alternating-current mains through a resistance coil of 200 ohms. The effective electromotive force between the mains is 1,000 volts and the frequency is 133 cycles per second, so that the factor ω is equal to 835.7 radians per second; the reactance of the condenser is 598.3 ohms (negative); the impedance of the circuit is 630.85 ohms; the current, according to equation 21, is 1.585 amperes; the current, according to equation 22, is 71° 34′ ahead of the electromotive force in phase; and the power delivered to the circuit is 1,000 volts

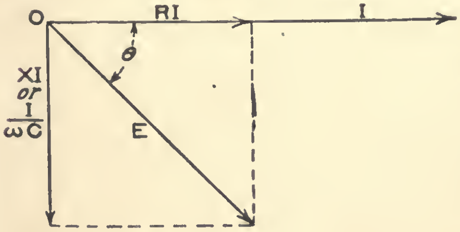


Fig. 49.

× 1.585 amperes × cos 71° 34′, which is equal to 501.2 watts ($= R I^2$).

If the above condenser is connected to the 1,000-volt 133-cycle mains through a wire of negligible resistance, then the current will be $\frac{1{,}000 \text{ volts}}{598.3 \text{ ohms}}$, or 1.671 amperes; the current will be very nearly 90° ahead of the electromotive force in phase; the power factor will be nearly zero; and of course the power delivered to the condenser will be nearly zero.

A circuit containing a condenser takes a little more power than is expended in the mere heating of the wire, namely $R I^2$, for some power is consumed in the insulating material between the condenser plates. In the above examples, this consumption of power in the insulating material of a condenser is neglected for the sake of simplicity.

CASE D. *Circuit in which the Inductance Reactance* ωL *is Balanced by the Capacity Reactance* $\frac{1}{\omega C}$. In this case equation 19 reduces to $I = \frac{E}{R}$; that is, the electromotive force acting upon the circuit has to overcome resistance only, as in case of the non-reactive circuit. This case, in which $\omega L - \frac{1}{\omega C}$ is equal to zero, is considered again in the following article, on resonance.

21. Electric Resonance. Consider a circuit, like the one shown in Fig. 40, containing a given resistance R, a given inductance L, and a given capacity C. Suppose that the alternator A is at first run at very slow speed so as to give very low frequency, and is then gradually increased in speed so as to cause the frequency to increase. This gradual increase of frequency will cause a gradual increase in the value of the factor ω (equal to 2π times the frequency); and as ω increases, the following relations between inductance reactance ωL and capacity reactance $\frac{1}{\omega C}$ will obtain:

(*a*) At first, when the frequency is very low (few cycles per second), the value of ω is small. Therefore the inductance reactance ωL is small;

the capacity reactance $\frac{1}{\omega C}$ is large; and the total net reactance $\omega L - \frac{1}{\omega C}$ is negative, and very nearly the same as $\frac{1}{\omega C}$ alone.

(*b*) As the frequency increases, the value of ω increases. Therefore the inductance reactance ωL increases; the capacity reactance $\frac{1}{\omega C}$ decreases; and the total net reactance $\omega L - \frac{1}{\omega C}$ decreases in value on account of the increase of ωL, and also on account of the decrease of $\frac{1}{\omega C}$. For a certain critical value of the frequency, ωL becomes equal to $\frac{1}{\omega C}$, so that the total net reactance is then zero. That is:

$$\omega L - \frac{1}{\omega C} = 0;$$

or,

$$\omega L = \frac{1}{\omega C};$$

or,

$$\omega^2 = \frac{1}{L C};$$

or,

$$\omega = \frac{1}{\sqrt{L C}};$$

or, since ω equals $2 \pi f'$, we have:

$$f' = \frac{1}{2 \pi \sqrt{L C}}, \qquad (24)$$

in which f' is the critical value of the frequency for which inductance reactance is balanced by capacity reactance in the given circuit, L being the inductance of the circuit, and C the capacity of the condenser. See Fig. 40.

(*c*) As the frequency increases beyond the critical value f', the inductance reactance ωL continues to increase; the capacity reactance continues to decrease; and the net reactance $\omega L - \frac{1}{\omega C}$, now positive in value, continues to increase in value.

Now, imagine the electromotive force of the alternator to be *constant in value*, although increasing in frequency as the alternator is speeded up. The current in the circuit will at first increase with increasing frequency until the critical frequency f' (see equation 24) is reached, and then the current will decrease in value as the frequency increases, a maximum value of current being produced at the critical frequency f'. This production of a maximum current at the critical frequency f' is called **electrical resonance.** At critical frequency the reactance $\omega L - \frac{1}{\omega C}$ is zero; and the general equation (19) reduces to $I = \frac{E}{R}$, as explained in Case D of article 20. That is, *the value of the current at the critical frequency is determined solely by the resistance of the circuit.*

The variation of current in a circuit like that shown in Fig. 40, with increasing frequency, electromotive force being kept constant in value, is shown graphically in Fig. 50, which is calculated from the following data: $E = 200$ volts, effective; $R = 2$ ohms; $L = 0.352$ henry; and $C = 20$ microfarads.

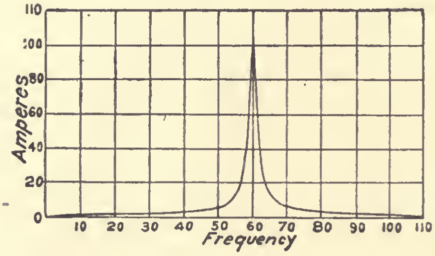


Fig. 50.

The critical frequency corresponding to these values of L and C is 60 cycles per second, according to equation 24. The maximum point of the curve is not a cusp, as would appear from the figure; but the curve is rounded at the top, the figure being drawn on too small a scale to show it.

The important physical features of electric resonance are explained in the next two articles, 22 and 23.

22. Multiplication of Electromotive Force by Resonance. When resonance exists in a circuit containing an inductance and a condenser in series, the alternating electromotive force $\omega L I$ between the terminals of the inductance, and the alternating electromotive force $I / \omega C$ between the terminals of the condenser, may each be much greater than the alternating electromotive force $R I$ which acts upon the circuit. This fact is easily understood by means of the mechanical analogue. If even a very weak periodic force act upon a weight which is suspended from a spiral spring, the weight will be set into violent vibration, provided the frequency of the force is the same as the proper frequency of oscillation of the body. The forces acting on the spring may reach enormously greater values than the periodic force which maintains the motion of the system. Moreover, the forces which act upon the weight to produce its up-and-down acceleration may reach values very much larger than the periodic force which maintains the motion.

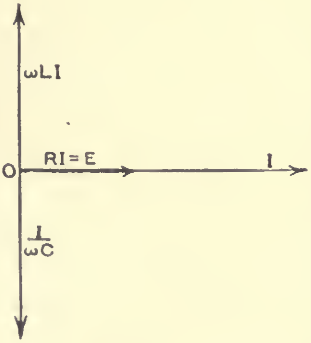


Fig. 51.

Example. A coil having an inductance of 0.352 henry and a resistance of 2 ohms, and a condenser of 20 microfarads capacity, are connected in series between alternating-current mains. The critical frequency of this circuit is 60 cycles per second, according to equation 24. The electromotive force between the mains is 200 volts, and its frequency is 60 cycles per second. The current in the circuit is $\frac{200 \text{ volts}}{2 \text{ ohms}}$, or 100 amperes, according to equation 19; the effective electromotive force between the condenser terminals is 13,270 volts effective ($= I / \omega C$); and the electromotive force between the terminals of the inductance is also 13,270 volts effective ($= \omega L I$).

The multiplication of electromotive force by resonance may be clearly understood with the help of the clock diagram, Fig. 51. The electromotive force $\omega L I$ required to overcome inductance reactance is equal and opposite to the electromotive force $I / \omega C$ required to overcome capacity reactance, as shown in Fig. 51, so that the geometric sum of $\omega L I$, $I / \omega C$, and RI is, simply, RI. A transmission line has both inductance and capacity, and therefore electric resonance may occur on a transmission line. The phenomena of a transmission line, however, are very greatly complicated by the fact that the capacity is distributed; and a simple

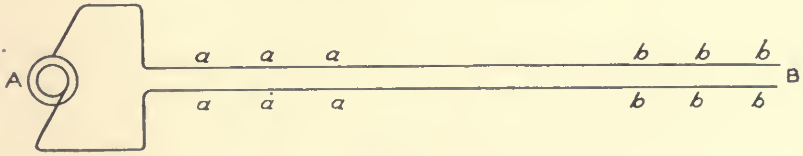


Fig. 52.

explanation of line resonance can be given only by approximation, as follows:

An alternator A, Fig. 52, delivers current to a long transmission line. The resonance effects are nearly independent of whether the receiving apparatus at B is connected or not. We shall therefore consider that the receiving apparatus is disconnected, and that the ends of the two transmission lines are insulated from each other.

A first approximation to the behavior of the line may be obtained by looking upon the distant end of the line *b b b* as a condenser purely and simply, while the near end of the line *a a a* is looked upon simply as an inductance. The transmission line shown in Fig. 52 is then equivalent to the combination shown in Fig. 53, which is identical with the combination shown in Fig. 40. The value of L may be taken as the inductance of, say, half the length of the line; and the capacity C may be taken as the capacity of the distant half of the transmission line. Then, if the alternator A gives a frequency equal to the critical value for these values of L and C, as per equation 24, we shall have resonance, and the electromotive force between the lines at the distant end (between terminals of C, Fig. 53) may be greatly in excess of the electromotive force of the alternator A. This condition actually occurs in the practical operation of long transmission lines; and it is not an uncommon thing to have as much as 11,000 volts at the receiving end of a long transmission line when the electromotive force of the generator is but 10,000 volts.

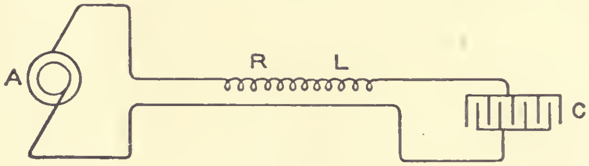


Fig. 53.

23. Multiplication of Current by Resonance. An alternator A, Fig. 54, delivers current to a circuit which divides at the points *a* and *b* into two branches, one branch containing an inductance L, and the other branch containing a capacity C, as shown. The two branches constitute a closed circuit in and of themselves; and if the frequency of the alternator is equal to the critical frequency of the circuit constituted by the two branches—that is, if the frequency of the alternator is equal to $\frac{1}{2\pi\sqrt{LC}}$, as per equation 24, then the small current I from the alternator will divide into two currents I_1 and I_2 in the respective branches, and the currents I_1 and I_2 may each be very much larger in value than the undivided current I. The fact is that, because of resonance, a very large current is made to surge back and forth around the closed circuit formed by the two branches.

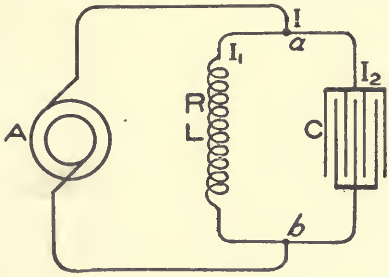


Fig. 54.

The multiplication of current by resonance may be clearly understood with the help of the clock diagram, Fig. 55.

The line OE represents the electromotive force between the branch points *a* and *b* (see Fig. 54); the line I_1 represents the lagging current which the electromotive force E produces in the branch containing the inductance; the line I_2 represents the leading current which the electromotive force E produces in the branch containing the condenser; and the line I, which is the geometric sum of I_1 and I_2, represents the total current in the undivided part of the circuit in Fig. 54.

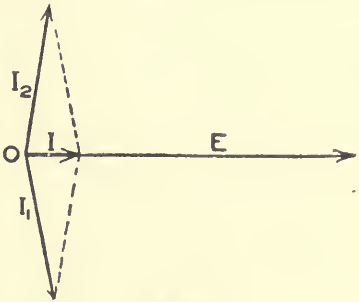


Fig. 55.

Example. Three similar 32-candle-power incandescent lamps A, B, and D, Fig. 56, each having 100 ohms resistance, are connected as shown, to 550-volt mains; L is an inductance of 0.597 henry; and C, a capacity of 2.49 microfarads. Then the current flowing through the lamp A is not quite 0.4 ampere, while one ampere of current flows through each of the lamps B and D.

24. Use of the Condenser as a Compensator for Lagging Current. An alternator may be designed to develop a certain effective electromotive force E, and to deliver a certain effective current I, at full load. Now, the permissible power output of such an alternator would be EI watts to a non-reactive circuit having unity power factor ($\cos\theta = 1$); but if the receiving circuit is reactive, the permissible power output of the alternator is only EI $\cos\theta$, where the power factor ($\cos\theta$) may in practice have a value of 8 / 10 or less. If a condenser C of sufficiently large capacity, Fig. 57, is connected to the terminals of an alternator A which delivers current to an inductive receiving circuit R L, the effect of L will be neutralized; the current delivered by A will be in phase with the electromotive force of A; and the permissible power output will be EI. The condenser is said to **compensate** for the lagging current taken by the inductive receiving circuit.

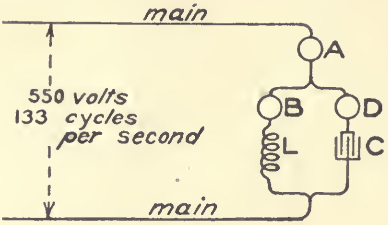


Fig. 56.

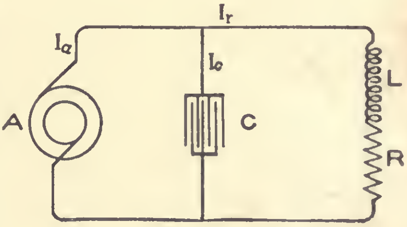


Fig. 57.

Another advantage (aside from the increase of the permissible power output of the generator) that would result from this compensating of lagging current by means of a condenser, is that the electromotive force of the alternator would not fall off so much with increase of load as is the case when lagging current is not compensated for. The cost, however, of large condensers is so great that their use for the compensation of lagging current is not commercially practicable.

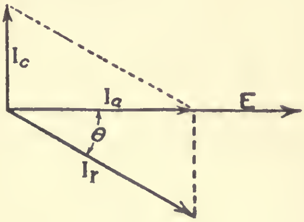


Fig. 58.

Let I_r be the current delivered to the receiving circuit R L, Fig. 57. Let I_c be the current delivered to the condenser C; this current is 90° ahead of E in phase. Let I_a be the current delivered by the alternator A. It is desired that I_a be in phase with E, as shown in Fig. 58. Let $\cos\theta$ be the power factor of the receiving circuit R L.

From Fig. 58 it is evident that I_c is equal and opposite to that component of I_r which is at right angles to E, namely, $I_r \sin \theta$. Therefore,

$$I_c = I_r \sin \theta. \qquad (i)$$

Now, I_c is equal to $E \,/\, \frac{1}{\omega C}$ $(= \omega C E)$, that is, is equal to the electromotive force between the condenser terminals divided by the reactance of the condenser. The value of $\sin \theta$ is $\frac{\omega L}{\sqrt{R^2 + \omega^2 L^2}}$; and $I_r = \frac{E}{\sqrt{R^2 + \omega^2 L^2}}$; so that, substituting the values of I_r and $\sin \theta$, equation i above becomes

$$\omega C E = \frac{\omega L E}{R^2 + \omega^2 L^2}; \qquad (ii)$$

whence

$$C = \frac{L}{R^2 + \omega^2 L^2}, \qquad \textbf{(25)}$$

in which R is the resistance (in ohms) of a receiving circuit; L is the inductance (in henrys) of the receiving circuit; ω is a factor equal to 2π times the frequency in cycles per second; and C is the capacity (in farads) of the condenser required to compensate for the lagging current delivered to the receiving circuit.

Example. An alternator having an electromotive force of 1,100 volts and a frequency of 60 cycles per second, delivers 102.4 amperes of current to a receiving circuit of which the power factor is 0.871 (9.35 ohms resistance and 0.014 henry inductance). A condenser to compensate for the lagging current in this case would have to have, according to equation 25, a capacity of 121.4 microfarads, calculated as follows:

$$C = \frac{0.014}{9.35^2 + (2\pi \times 60)^2 \times 0.014^2} \text{ farads} = 0.0001214 \text{ farad}$$
$$= 121.4 \text{ microfarads.}$$

This condenser would take from the mains a current of 50.34 amperes, which would be 90° ahead of the electromotive force in phase, and this current would be equal and opposite to the wattless component of the 102.4 amperes of current delivered to the inductive circuit. Such a condenser would require about 114,000 leaves of tin foil 8 inches × 10 inches, separated by 114,000 leaves of paraffined paper, each 0.03 inch in thickness. This would give a stack of condenser leaves of about 400 feet total thickness; and the cost of material and labor would be at least $10 per microfarad.

25. Circuits in Series. An alternator A, Fig. 59, delivers current to two coils (or elements) in series as shown. Let R_1 be the resistance, and X_1 the reactance, of coil No. 1. Let R_2 be the resistance, and X_2 the reactance, of coil No. 2. Let I be the current flowing through the circuit; E the electromotive force between the mains; E_1 the electromotive force between the terminals of coil No.1; and E_2 the electromotive force between the terminals of coil No. 2. Let θ be the phase difference between E and I; θ_1 the phase difference between E_1 and I; and θ_2 the phase difference between E_2 and I, as shown in Fig. 60.

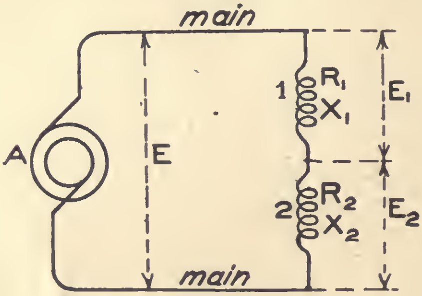


Fig. 59.

Of course θ_1 is the angle whose tangent is X_1/R_1; θ_2 is the angle whose tangent is X_2/R_2; and θ is the angle whose tangent is $(X_1+X_2)/(R_1+R_2)$, according to equation 22.

The general relation between E_1, E_2, and E is shown sufficiently by the clock diagram, Fig. 60, and this general relation need not be further discussed. Two very important practical cases, however, arise, which involve circuits in series—namely, the loss of electromotive force in transmission lines, and the loss of electromotive force in alternator armatures.

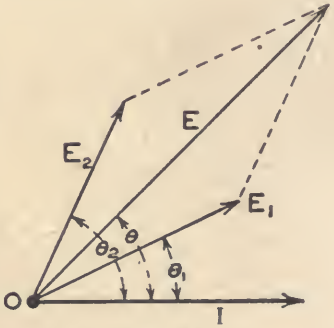
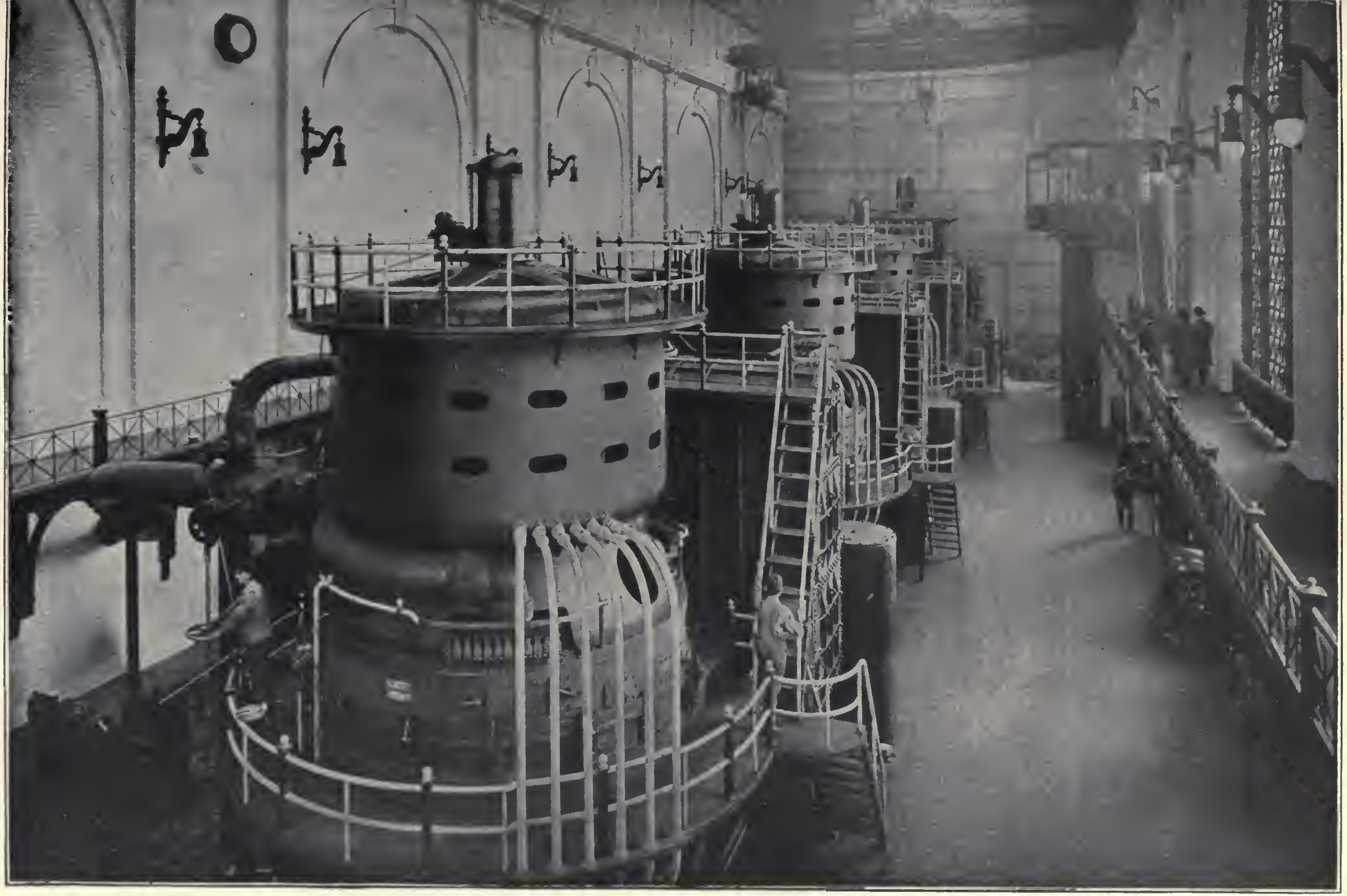


Fig. 60.

26. Electromotive Force Losses in Transmission Lines. An alternator of which the electromotive force is E, delivers current over a transmission line of which the resistance is R_1 and



SOME OF THE GENERATORS IN THE WORLD'S LARGEST CENTRAL STATION

View taken in Fisk Street Station of the Commonwealth Electric Company, Chicago, Ill. The total capacity of the station is 176,000 kw. Of the four turbo-generators here shown, that furthest in the background has a capacity of 9,000 kw; the other three, 7,500 kw. each.

the reactance (inductance reactance) is X_1, to a receiving circuit of which the resistance is R_2 and the reactance is X_2. The total electromotive force used to overcome the resistance and reactance of the transmission line is E_1, and the electromotive force between the terminals of the receiving circuit is E_2. The current delivered is I. Then the general relation between E, E_1, and E_2 is as shown in Fig. 60, *except that E_2 is usually much larger than E_1 in value.* There are three interesting and simple special cases of electromotive force losses in transmission lines, as follows:*

CASE 1. *When the receiving circuit is non-reactive.* In this case the electromotive force E_2 between the terminals of the receiving circuit is in phase with I, and the general diagram of Fig. 60 takes the form shown in Fig. 61. The total electromotive force E_1 consumed in the line, is sometimes called the **impedance loss**; and its two components R_1 I and X_1 I, as shown in Fig. 61, are called the **resistance loss** and the **reactance loss,** respectively. Now, a careful inspection of Fig. 61 makes it evident that the numerical difference in value of E and E_2 is very nearly equal to the resistance loss in the line, R_1 I; and that the reactance loss in the line, X_1 I, has little to do with the difference in value of E and E_2. Therefore, *when the receiving circuit is non-reactive, the difference in value between generator electromotive force E and receiver electromotive force E_2 is sensibly equal to the resistance loss of electromotive force in the line, and sensibly independent of the reactance loss of electromotive force in the line.*

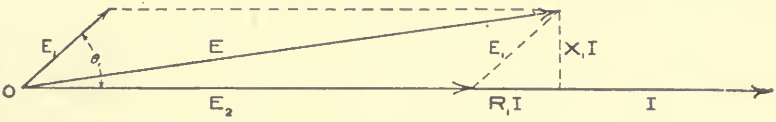


Fig. 61.

CASE 2. *When the receiving circuit is highly reactive.* In this case the electromotive force E_2 between the terminals of the receiving circuit is nearly 90° ahead of I in phase, and the general diagram of Fig. 60 takes the form shown in Fig. 62.

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* NOTE. This discussion applies to comparatively short lines, ten miles or less in length, inasmuch as the capacity of the line is not here taken into account.

A careful inspection of Fig. 62 makes it evident that the difference in value of E and E_2 is very nearly equal to the reactance loss in the line, X_1 I; and that the resistance loss in the line, R_1 I, has little to do with the difference in value of E and E_2. Therefore, *when the receiving circuit is highly reactive, the numerical difference in value between generator electromotive force E and receiver electromotive force E_2 is sensibly equal to the reactance loss of electromotive force in the line, and sensibly independent of the resistance loss of electromotive force in the line.*

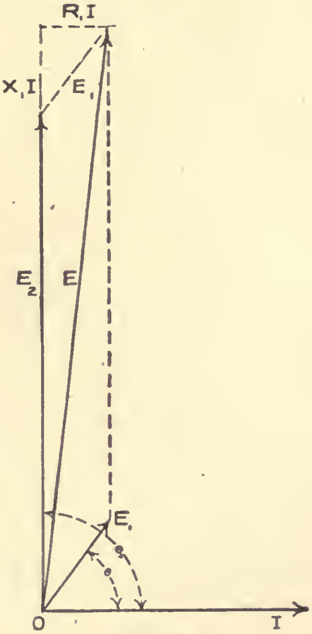

Fig. 62.

CASE 3. *When the receiving circuit has large capacity reactance.* In this case the electromotive force E_2 between the terminals of the receiving circuit is nearly 90° behind I in phase, and the general diagram of Fig. 60 takes the form shown in Fig. 63. A careful inspection of Fig. 63 makes it evident that the difference in value of E and E_2 is very nearly equal to the reactance loss in the line, X_1 I, *and that this reactance loss is added to the generator electromotive force E to give the receiver electromotive force E_2.* Inspection of Fig. 63 shows furthermore that the resistance loss in the line, R_1 I, has little to do with the difference in value of E and E_2. Therefore, *when the receiving circuit has a high capacity reactance, the reactance loss in the line is sensibly equal to the rise in value of the electromotive force between generator and receiver, and this rise in value is sensibly independent of the resistance loss of electromotive force in the line.* Of course, it is confusing to speak of the electromotive force X_1 I as reactance *loss* when the receiving circuit has a high capacity reactance; it would be better in this case to speak of X_1 I as the reactance *gain* of electromotive force in the line.

27. Electromotive Force Losses in Alternator Armatures. Let E be the total induced electromotive force in the armature of an alternator. A portion E_1 of this electromotive force is used to overcome the resistance R_1 and the reactance X_1 of the armature; and the remainder E_2 is available at the terminals of the alternator for producing current in the outside circuit, of which the resistance is R_2 and the reactance is X_2. The general relation between E, E_1, and E_2 is as shown in Fig. 60, *except that E_2 is usually much larger than E_1 in value.* There are three interesting and simple special cases of electromotive force losses in alternator armatures, as follows:

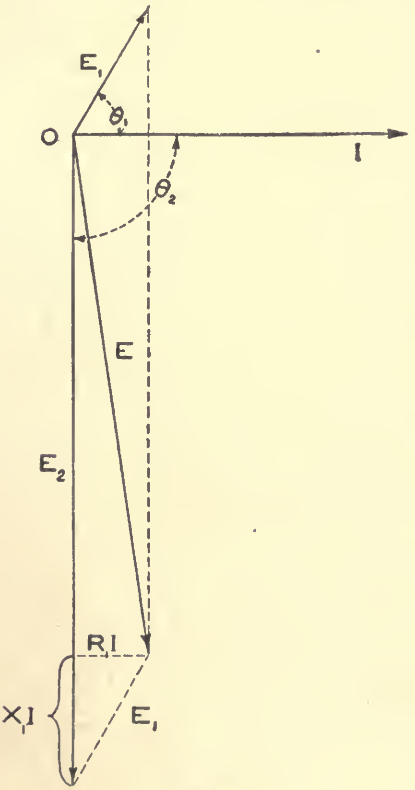

Fig. 63.

Case 1. *When the receiving circuit is non-reactive.* In this case the electromotive force E_2 between the terminals of the alternator is in phase with the current I delivered by the machine, and the general diagram of Fig. 60 takes the form shown in Fig. 61, from which it is evident that when the receiving circuit is non-reactive, the numerical difference in value between the total induced electromotive force E and the terminal electromotive force E_2 of the machine is sensibly equal to the resistance loss of electromotive force, R_1 I, in the armature, and sensibly independent of the reactance loss of electromotive force, X_1 I, in the armature.

Case 2. *When the receiving circuit is highly reactive.* In this case the electromotive force E_2 between the terminals of the alternator is nearly 90° ahead of I in phase, and the general diagram of Fig. 60 takes the form shown in Fig. 62, from which it is evident that when the receiving circuit is highly reactive the numerical difference in value between the total induced electromotive force E and the terminal electromotive force E_2 of the machine is sensibly equal to the reactance loss of electromotive force, X_1 I, in the armature, and sensibly independent of the resistance loss of electromotive force, R_1 I, in the armature.

CASE 3. *When the receiving circuit has large capacity reactance.* In this case the electromotive force E_2 between the terminals of the alternator is nearly 90° behind I in phase, and the general diagram of Fig. 60 takes the form shown in Fig. 63, from which it is evident that when the receiving circuit has a high capacity reactance the difference in value between E and E_2 is sensibly equal to X_1 I, *E_2 being larger than E*, and sensibly independent of the resistance loss of electromotive force, R_1 I, in the armature.

MEASURING INSTRUMENTS.

28. The Hot-wire Ammeter and Voltmeter.* In these instruments the current to be measured is sent through a stretched wire. The wire, heated by the current, lengthens, and actuates a pointer which plays over a divided scale.

The hot-wire instrument, when calibrated by continuous currents, indicates effective values of alternating currents; and when calibrated by continuous electromotive forces, it indicates effective values of alternating electromotive forces.

PROOF. Consider an alternating current and a continuous current C which give the same reading. *These currents generate heat in the wire at the same average rate.* This rate is RC^2 for the continuous current, and $R \times$ average i^2 for the alternating current, i being the instantaneous value of the alternating current. Therefore $RC^2 = R \times$ average i^2; or $C^2 =$ average i^2; or $C = \sqrt{\text{average } i^2}$.

The proof for electromotive forces is similar to this proof for currents.

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*NOTE. All voltmeters except the electrostatic voltmeter are essentially ammeters; that is, the electromotive force to be measured produces a current which actuates the instrument. The scale over which the pointer plays, may be arranged to indicate either the value of the current flowing through the instrument, or the value of the electromotive force acting between the terminals of the instrument.

Fig. 64 is a general view of the hot-wire ammeter of the Stanley Electric Manufacturing Company. The current to be measured passes through a short wire of platinum silver alloy which is placed, properly protected, in the circuit; and the elongation of the wire due to the heating effect of the current actuates the pointer, which is delicately mounted in jeweled bearings. Only a small portion of the current measured passes through the hot wire, but the main portion of the current passes through a shunt of low resistance.

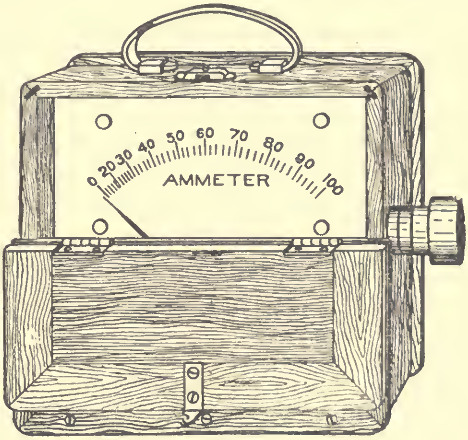


Fig. 64.

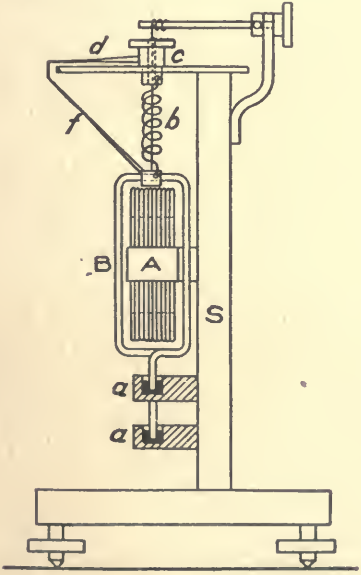


Fig. 65a.

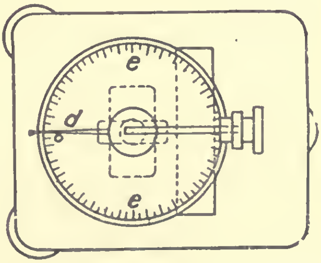


Fig. 65b.

29. The Electro-dynamometer Used as an Ammeter. The electro-dynamometer consists of a fixed coil and a movable coil connected in series, through both of which the current to be measured flows. The current causes the fixed coil to exert a certain

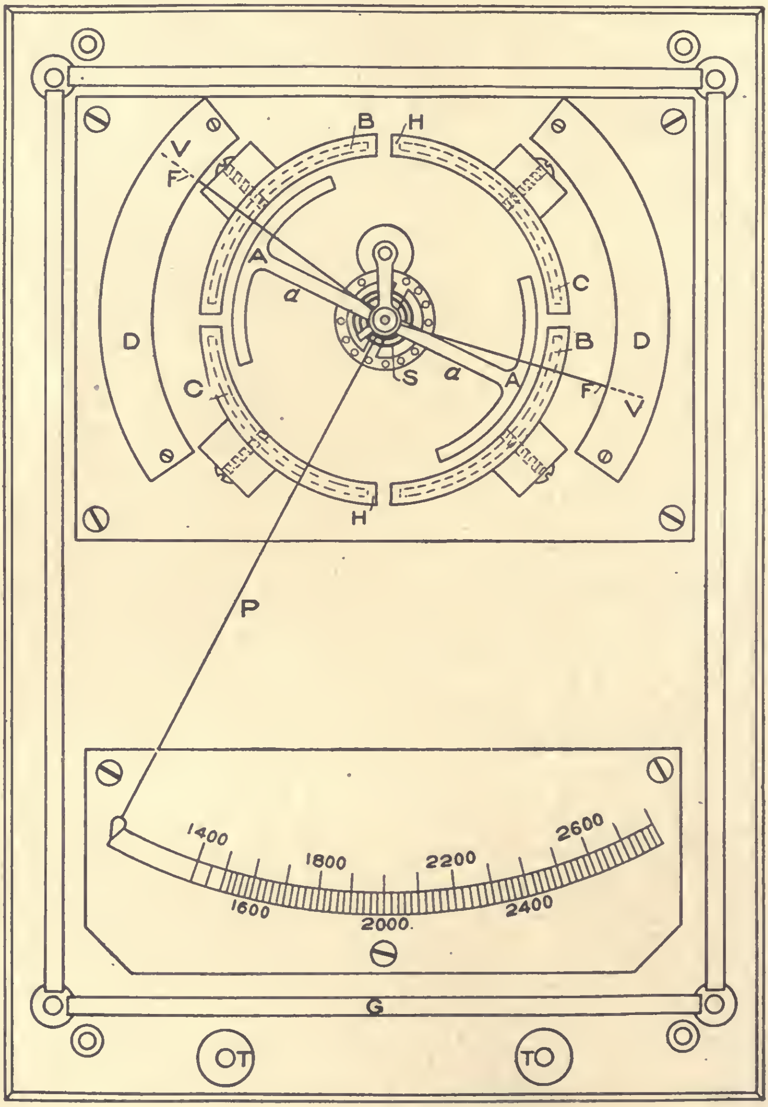


Fig. 66.

force upon the movable coil; and the value of the current is determined either (*a*) by observing the angle ϕ through which a helical spring must be twisted (by hand) in order to balance the above-mentioned force, or (*b*) by allowing the force to turn the movable coil, and move a pointer over a divided scale. In the Siemens electro-dynamometer, method *a* is employed; in many commercial forms of electro-dynamometer, method *b* is employed.

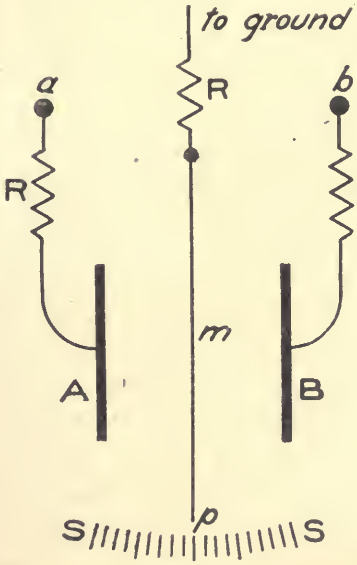


Fig. 67.

The essential features of the Siemens electro-dynamometer are shown in Figs. 65*a* and 65*b*. The stationary coil A is supported by a clamp attached to the standard S; and the movable coil B is hung by a thread, the plane of coil B being at right angles to the plane of coil A. The terminals of the movable coil dip into cups of mercury *a a*, and the current to be measured is sent through both coils in series. The force action between the coils is balanced by carefully turning the torsion head *c* by hand, thus twisting a helical spring *b*, one end of which is attached to the coil B and the other to the torsion head *c*. The observed angle of twist necessary to bring the swinging coil to its zero position, is read off by means of the pointer *d* and the graduated scale *e*. The pointer *f* attached to the coil shows when it has been brought to its zero position. The observed angle of twist of the helical spring affords a measure of the force action between the coils, and the current is proportional to the square root of this angle of twist. That is,

$$I = k\sqrt{\phi}, \qquad (26)$$

in which I is the effective value of the alternating current; ϕ is the observed angle of twist of the helical spring *b*; and *k* is a constant called the **reduction factor** of the instrument.

Example. A twist of 220° is required to balance the force action of 18.8 amperes in a certain Siemens electro-dynamometer, so that the reduction factor *k* of the instrument is, by equation

26, equal to 18.8 amperes divided by $\sqrt{220}$, or 1.267. A certain current to be measured requires a twist of the torsion head of 165°, hence the value of the current is equal to 1.267 multiplied by $\sqrt{165}$, or 16.28 amperes.

The electro-dynamometer, when standardized by direct currents, indicates effective values of alternating currents.

PROOF. A given deflection of the suspended coil depends upon a definite average or constant force action between the coils. The constant force action due to a constant current C is kC^2 (proportional to C^2); and the average force action due to an alternating current is $k \times$ average i^2; so that if these currents give equal deflections, we have $kC^2 = k \times$ average i^2; or $C^2 =$ average i^2; or $C = \sqrt{\text{average } i^2}$.

The electro-dynamometer is the standard instrument for measuring alternating currents, and it is always used in accurate measurements.

30. The Electro-dynamometer Used as a Voltmeter. When used as a voltmeter the coils of the electro-dynamometer are made of fine wire, and an auxiliary non-inductive resistance is usually connected in series with the coils.

When the inductance of the electro-dynamometer coils is small, such an instrument, when calibrated by continuous electromotive forces, indicates effective values of alternating electromotive forces.

When it is certain that the inductance of an electro-dynamometer is negligibly small, the instrument may be used in refined alternating electromotive force measurements.

Inductance Error of the Electro-dynamometer Used as a Voltmeter. An electro-dynamometer which has been calibrated by continuous electromotive forces indicates less than the effective value of an alternating electromotive force. Let $\mathbf{E}$ be the reading of an electro-dynamometer voltmeter when an alternating electromotive force (harmonic), of which the effective value is E, is connected to its terminals. That is, $\mathbf{E}$ is the continuous electromotive force which gives the same deflection as E; and, since E gives the same deflection as $\mathbf{E}$, it follows that the effective current produced by E is equal to the continuous current produced by $\mathbf{E}$; that is,

$$\frac{\mathbf{E}}{R} = \frac{E}{\sqrt{R^2 + \omega^2 L^2}}, \qquad \text{(a)}$$

in which R is the total resistance of the instrument; L its inductance; and $\omega = 2\pi f$, where f is the frequency of the alternating electromotive force. Solving equation (a) for E, we have,

$$E = \frac{\sqrt{R^2 + \omega^2 L^2}}{R} E \qquad \text{(b)}$$

That is, the reading of the instrument must be multiplied by the factor

$$\frac{\sqrt{R^2 + \omega^2 L^2}}{R}$$

to give the true effective value of a harmonic alternating electromotive force.

Plunger-type voltmeters also have inductance errors.

31. *The Electrostatic Voltmeter.* Two metal plates connected to the terminals of a battery, or to any source of electromotive force, attract each other with a force strictly proportional to the square of the electromotive force. This principle is applied in the **electrostatic voltmeter,** which consists essentially of a fixed metal plate and a movable plate delicately mounted on a jeweled pivot. The movable plate carries a pointer, which plays over a divided scale. The electromotive force to be measured is connected between the fixed plate and the movable plate; and the electrical attraction between the plates causes the movable plate to turn about its supporting pivot and move the pointer. *Such an instrument, when calibrated by continuous electromotive force, indicates effective values of alternating electromotive force.*

Proof. A given deflection of the movable plate depends upon a definite average or constant force action between the two plates. The force action due to a constant electromotive force E is kE^2 (that is, the force is proportional to E^2); and the average force action due to an alternating electromotive force e is $k \times$ average e^2. If these electromotive forces give equal deflections, the constant force kE must be equal to the average force $k \times$ average e^2; that is,

$$kE^2 = k \text{ average } e^2;$$

or, $$E^2 = \text{average } e^2;$$

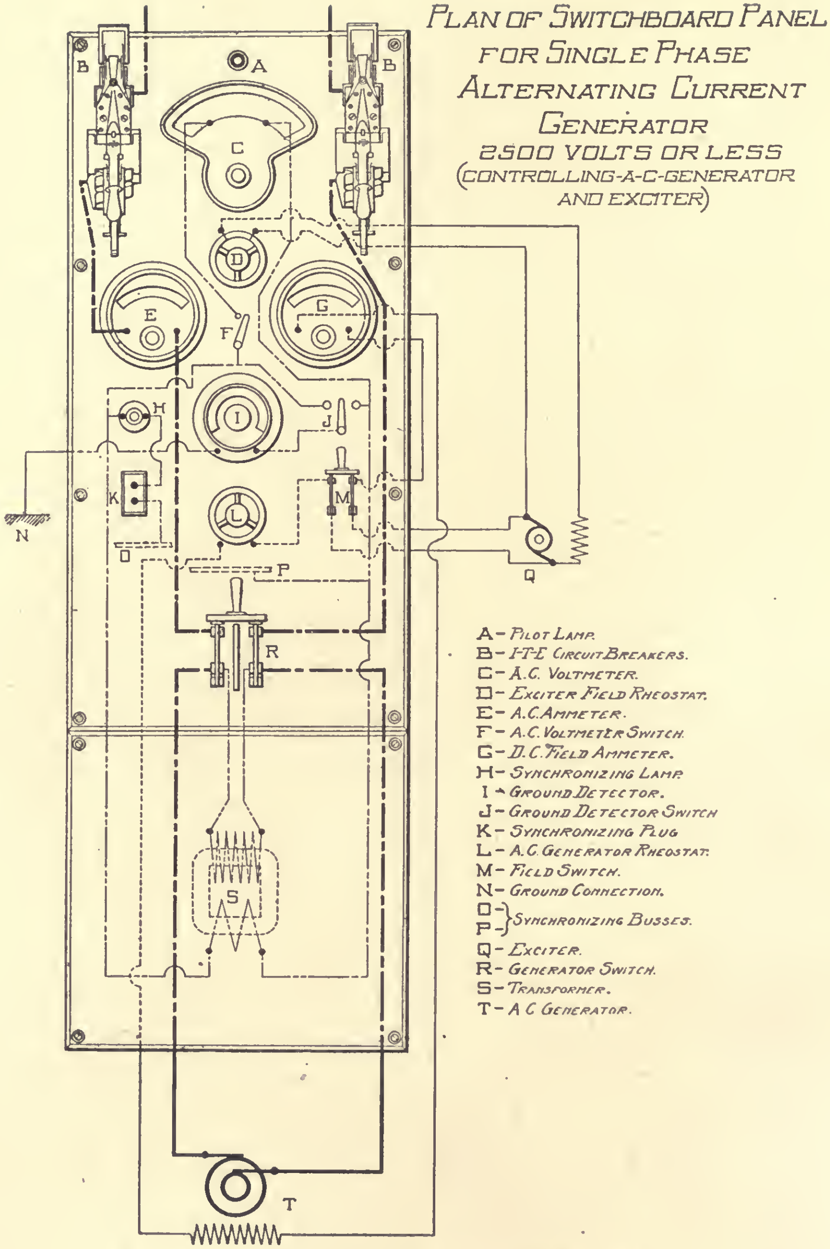
or, $$\sqrt{\text{average } e^2} = E.$$

This is the standard instrument for measuring alternating electromotive forces, especially very high ones.

Fig. 66 represents the essential parts of the **Stanley electrostatic voltmeter.** A pair of light metal plates AA are carried by an arm *aa*, which is supported in jeweled bearings and held in a certain position by a delicate hair spring S. To these movable plates AA and the arm *aa*, are attached a pointer P and two fingers FF. The pointer moves over a scale calibrated to indicate volts; and the fingers FF carry two thin vanes VV, which move, without touching, in two narrow air chambers DD, the latter serving as dash-pots or dampeners to bring the movable plate quickly to rest. One terminal of the circuit whose electromotive force is to be measured, is connected through the hair spring to the plates AA; and the other terminal of the circuit, is connected to the fixed metal plates CC; these plates are encased in a sheathing of hard rubber HH, which tends to prevent sparking across from CC to AA. The action of the electromotive force is to cause the plates CC to attract the movable plates AA, and this moves the pointer P over the scale of volts. The metal plates BB are connected by a wire to the hair spring, and thence to the plates AA. The object of the plates BB is to shield the movable plates AA from all external objects except the attracting plates CC.

The **electrostatic ground detector** is a modified electrostatic voltmeter. Its essential features are shown in Fig. 67. Two metal plates A and B are connected to the two mains *a* and *b* (usually through two high resistances RR); and a light movable metal plate *m*, suspended between A and B, is connected to ground (usually through a high resistance R). If both lines are equally well insulated from ground, the plates A and B are each at the same electrical pressure or potential, and they attract the plate *m* equally, so that the plate *m* hangs midway between them. If one of the mains, say *a*, is grounded, its pressure or potential becomes equal to the potential of *m*, so that plate A no longer attracts *m*, and the plate *m* is therefore pulled to the right by the attraction of B. This movement is indicated by a pointer *p*.

The same results may be accomplished, when the plate *m* is entirely insulated from the ground, by having a grounded auxiliary stationary plate near *m*.



PLAN OF SWITCHBOARD PANEL.

The Cutter Company.

ALTERNATING CURRENT MACHINERY.

PART II.

VOLTMETERS (Continued).

The essential features and mode of connection of the General Electric Company's electrostatic ground detector are shown in Fig. 68; and a general view of the instrument, with cover removed, is shown in Fig. 69.

Fig. 70 shows the connection of two instruments to three-phase mains.

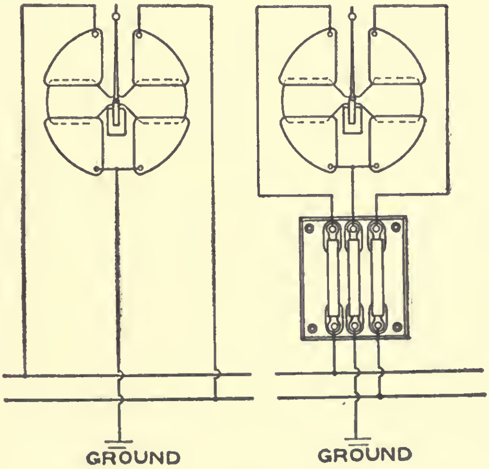


Fig. 68.

32. The Spark Gauge. The high electromotive forces used in break-down tests are usually measured by means of the spark gauge. This consists of an adjustable air gap, which is changed until the electromotive force to be measured is just able to strike across in the form of a spark. The electromotive force is then taken from empirical tables based upon previous measurements of the electromotive force required to strike across various widths of gap. In the spark gauge of the General Electric Company, the spark

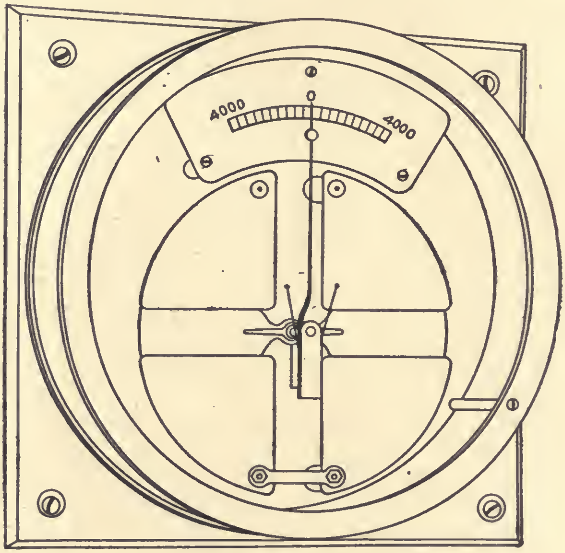


Fig. 69.

gap is between metal points, one of which is attached to a micrometer screw whereby the gap space may be adjusted and measured. The striking distance in any spark gauge varies greatly with the condition of the points. It is therefore necessary to see that the points are well polished before taking measurements.

Fig. 71 is a general view of the high-potential testing transformer of the General Electric Company. The spark gauge is shown mounted on top of the instrument. While being used, the gauge is protected by a cover (shown re-

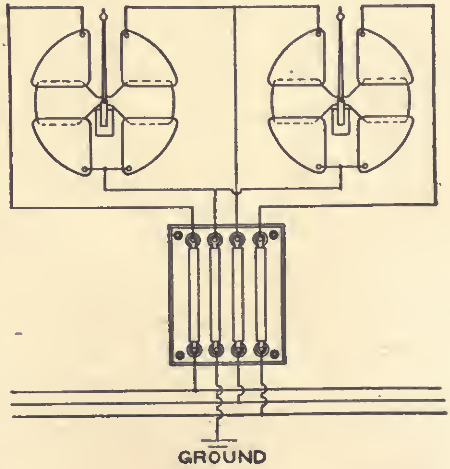


Fig. 70.

moved in Fig. 71). The function of this cover is to keep the observer's fingers from the dangerous high-potential points of the gauge; and the cover, moreover, acts as a switch that automatically disconnects the gauge from the high-potential terminals of the transformer when the cover is removed.

33. Plunger-Type Ammeters and Voltmeters. In instruments of this type the current to be measured passes through a coil of wire that magnetizes and attracts a movable piece of soft iron to which the pointer is fixed.

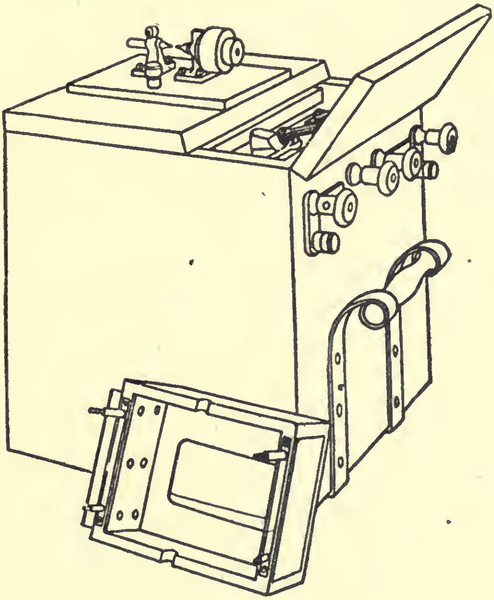


Fig. 71.

When a plunger-type instrument is calibrated, using direct-electromotive force (or current), it does not indicate effective values of alternating electromotive forces (or currents) accurately. A plunger-type meter (ammeter or voltmeter) should be calibrated, using alternating current of the same frequency as that for which the meter is afterwards to be used, and of the same wave shape. Thus, if a plunger instrument is to be used as an ammeter for alternating currents of a given wave shape and frequency it should be calibrated by currents of this wave shape and frequency, these currents, for the purpose of the calibration, being measured by a standard alternating-current ammeter, such as an electro-dynamometer.

The indications of a plunger instrument, however, do not vary greatly with wave shape and frequency, and such instruments are practically correct for any ordinary wave shape and frequency.

The **Thomson inclined-coil meter** of the General Electric Co. is essentially of the plunger type. The working parts of this instrument are shown in Fig 72. A coil A, through which flows the current to be measured, is mounted with its axis inclined as shown. A vertical spindle mounted in jewel bearings and controlled by a hair spring, passes through the coil ; and to this spindle are fixed a pointer *b* and a vane of thin sheet iron *a*. This vane of iron is mounted obliquely to the spindle. When the pointer is at the zero point of the scale, the iron vane *a* lies nearly across the axis of the coil ; and when a current passes through the coil, the vane tends to turn until it is parallel to the axis of the coil, thus turning the spindle and moving the attached pointer over the calibrated scale.

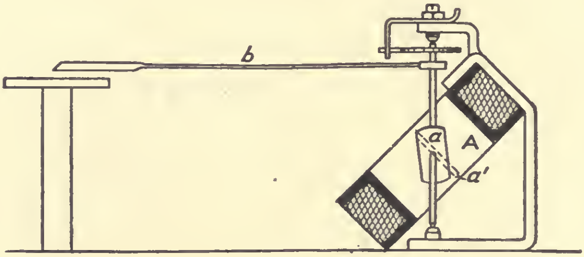


Fig. 72.

Fig. 73 is a general view of a Thomson inclined-coil ammeter, and Fig. 74 is a view of the working parts of the instrument. The structural details of the inclined-coil voltmeter are identical with those of the ammeter, except that the voltmeter has fine wire in the inclined coil and usually an auxiliary non-inductive resistance in series with the inclined coil.

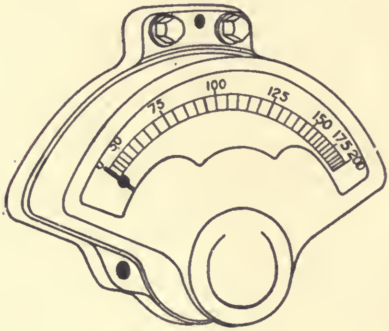


Fig. 73.

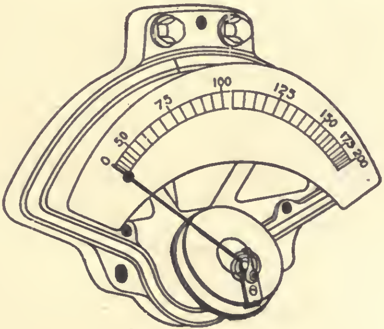
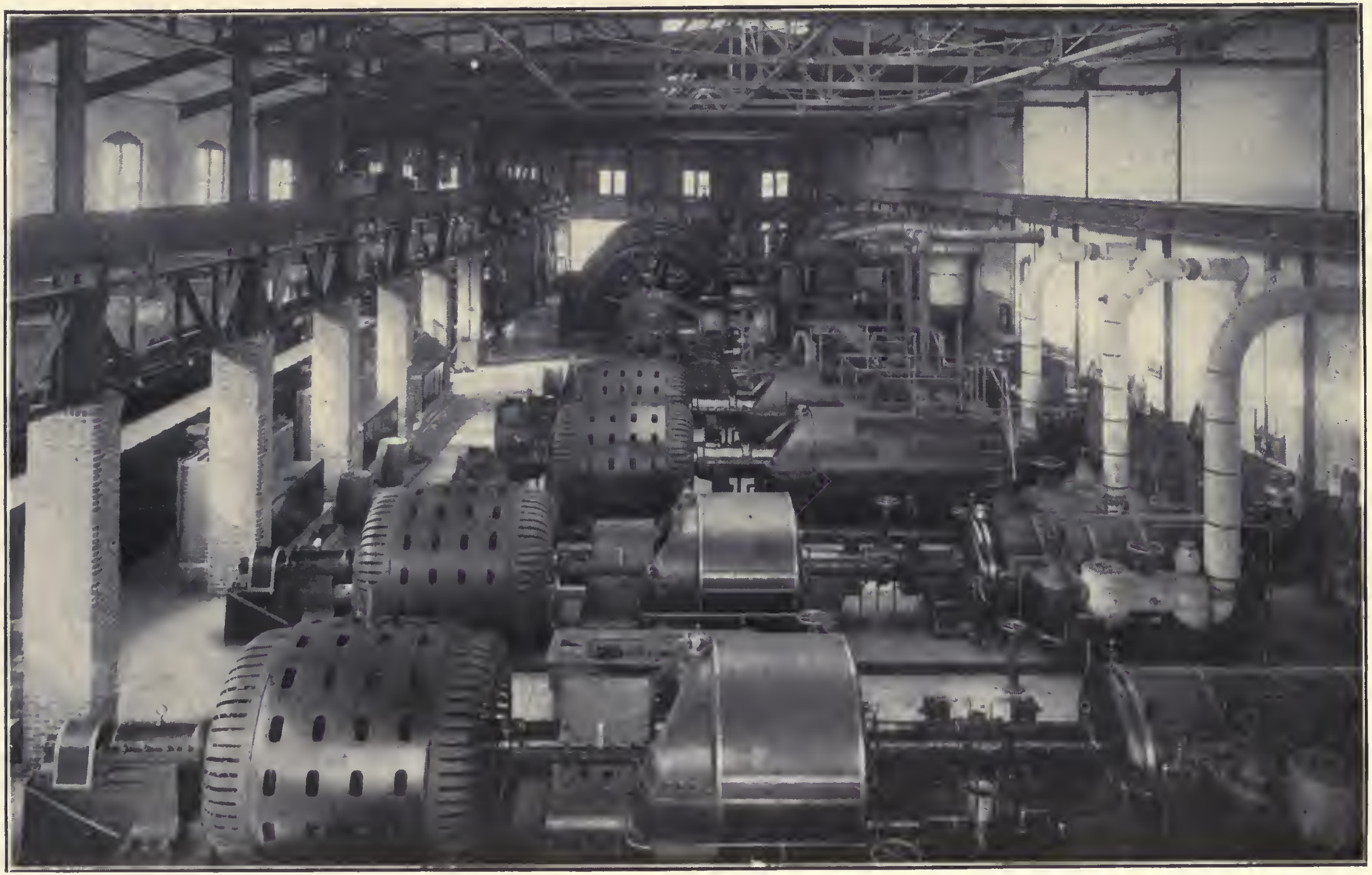


Fig. 74.



GROUP OF WESTINGHOUSE-PARSONS TURBINE UNITS IN THE 16,000 H. P. PLANT OF THE PHILADELPHIA RAPID TRANSIT CO.

The Westinghouse Machine Co.

34. Measurement of Power in Alternating Circuits*. *The Three-Voltmeter Method.* A non-inductive resistance R, Fig. 75, is connected in series with the circuit *bc* (the primary coil of a transformer, for example), in which the power P (to be determined) is expended. The electromotive forces E_1 between *ab*, E_2 between *bc*, and E_3 between *ac*, may be observed by means of one voltmeter, a three-way switch being used to enable the voltmeter terminals to be quickly transferred from *ab* to *bc* to *ac*. The three readings should be taken as nearly simultaneously as possible. Then

$$P = \frac{E_3^2 - E_1^2 - E_2^2}{2R}. \qquad (27)$$

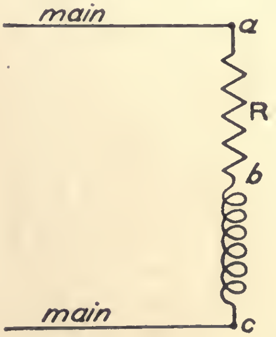


Fig. 75.

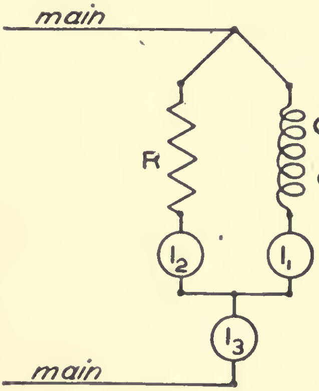


Fig. 76.

This equation is true whatever the wave shape of the electromotive force or current, and whatever the reactance of the circuit *bc* may be.

PROOF.—Let e_1, e_2, and e_3 be the instantaneous electromotive forces between *ab*, *bc*, and *ac*, respectively; then

$$e_3 = e_1 + e_2\,; \qquad (i)$$

or,

$$e_3^2 = e_1^2 + 2e_1e_2 + e_2^2\,; \qquad (ii)$$

or,

$$\text{average } e_3^2 = \text{average } e_1^2 + 2 \text{ average } e_1e_2 + \text{average } e_2^2. \qquad (iii)$$

But,

$$E_3^2 = \text{average } e_3^2,\ E_1^2 = \text{average } e_1^2, \text{ and } E_2^2 = \text{average } e_2^2.$$

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* NOTE.—In alternating circuits power cannot be measured by means of an ammeter and a voltmeter, as in the case of direct current, for the reason that the power expended is, in general, less than the product of effective electromotive force and effective current, on account of the difference in phase of the current and the electromotive force.

Further, $\frac{e_1}{R}$ is the instantaneous current in *abc;* $\frac{e_1}{R}e_2$ is the instantaneous power expended in *bc;* and average $(\frac{e_1}{R}e_2)$, or $\frac{1}{R} \times$ average (e_1e_2) is the average power P expended in *bc*, so that average $(e_1e_2) = RP$. Therefore equation *iii* becomes

$$E_3^2 = E_1^2 + 2RP + E_2^2 ; \qquad (iv)$$

or,

$$P = \frac{E_3^2 - E_1^2 - E_2^2}{2R}.$$

The three-voltmeter method is subject to large errors. To obtain the most accurate results the electromotive forces E_1 and E_2 must be nearly equal. The method is inconvenient in application, and is seldom used in practice.

35. *The Three-Ammeter Method.* The circuit CC, Fig. 76, in which the power P to be measured is expended, is connected in parallel with a non-inductive resistance R ; and three ammeters are placed as shown. Then

$$P = \frac{R}{2}(I_3^2 - I_1^2 - I_2^2) \qquad (28)$$

in which I_1, I_2 and I_3 are the currents indicated by the three ammeters.

Proof.—Let i_1, i_2 and i_3 be the instantaneous values of the currents I_1, I_2, and I_3. Then

$$i_3 = i_1 + i_2 \qquad (i)$$

or,

$$i_3^2 = i_1^2 + 2i_1i_2 + i_2^2) ; \qquad (ii)$$

or,

$$\text{average } i_3^2 = \text{average } i_1^2 + 2 \text{ average } (i_1i_2) + \text{average } i_2^2. \qquad (iii)$$

But I_1^2 = average i_1^2 ; I_2^2 = average i_2^2 ; and I_3^2 = average i_3^2.

Further, the instantaneous electromotive force between the terminals of R or of CC is Ri_2, so that Ri_2i_1 is the instantaneous power expended in CC, and R × average (i_1i_2) is the average power P expended in CC. Therefore average $(i_1i_2) = \frac{P}{R}$, and equation *iii* becomes:

$$I_3^2 = I_1^2 + \frac{2P}{R} + I_2^2 ; \qquad (iv)$$

or,

$$P = \frac{R}{2}(I_3^2 - I_1^2 - I_2^2).$$

The three-ammeter method is more convenient in practice than the three-voltmeter method because it does not require a supply of alternating current at a voltage higher than that for which the apparatus CC, Fig. 76, is designed. This method of measuring power, is however, little used in practice.

36. The Wattmeter. A good wattmeter is the standard instrument for measuring power in alternating current circuits. The wattmeter is an electrodynamometer, of which one coil a, Fig. 77, made of fine wire, is connected to the terminals of the circuit CC, in which the power to be measured is expended. The other coil b, made of large wire, is connected in series with CC, as shown. The fine-wire coil a is movable, and carries the pointer which indicates on a divided scale the watts expended in CC.

Such an instrument when calibrated with continuous current and electromotive force indicates power accurately when used with alternating currents, provided the inductance of the circuit ar *is small.* This is true whatever the wave shape of the electromotive force or current, and whatever the character of the receiving circuit CC may be. Thus the circuit CC may have any reactance.

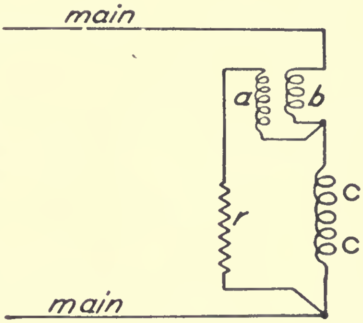


Fig. 77.

Proof.—A given deflection of the movable coil a depends upon a certain average or constant force action between the coils. Consider a continuous electromotive force E, which produces a current $\frac{E}{r}$ in a, and a current C in CC and b. The force action between the coils is proportional to the product of the currents in a and b; that is, the force action is $k \times \frac{E}{r} \times C$, where k is a constant.

Consider an alternating electromotive force of which the instantaneous value is e: this produces a current $\frac{e}{r}$ through a (provided the inductance of a is zero), and a current i in CC and b. The instantaneous force action between the coils is $k \times \frac{e}{r} \times i$; and the average force action is $\frac{k}{r} \times$ average (ei). If this alternating electromotive force gives the same deflection as the continuous electromotive force, then

$$\frac{k}{r} \times \text{average } (ei) = \frac{k}{r} \text{EC} ;$$

or.

$$\text{average } (ei) = \text{EC}$$

That is, the given deflection indicates the same power whether the currents are alternating or direct.

Let P be the true power delivered to the circuit CC as measured by a wattmeter; let E be the effective electromotive force between the terminals of CC as measured by an alternating-current voltmeter; and let I be the effective current flowing in CC as measured by an alternating-current ammeter.

Then the ratio $\frac{P}{EI}$ is called the *power factor* of the circuit CC.

Examples. The primary coil of a certain 5-kilowatt transformer with secondary coil open-circuited takes 0.14 ampere from 1,000-volt mains; and the power as measured by a wattmeter is 100 watts. The power factor, therefore, is,

$$\frac{100 \text{ watts}}{1{,}000 \text{ volts} \times 0.14 \text{ ampere}} = 0.714.$$

One of the stator circuits of polyphase induction motor running unloaded has a power factor of 0.6. It takes 2 amperes from 200-volt mains. The true power, as would be indicated by a wattmeter, is,

$$P = 200 \text{ volts} \times 2 \text{ amperes} \times 0.6 = 240 \text{ watts}.$$

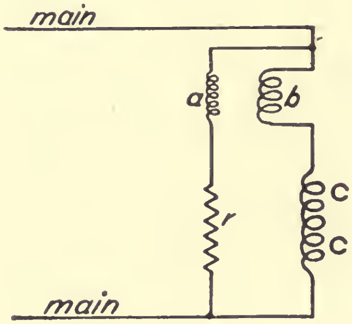


Fig. 78.

If a wattmeter is connected as shown in Fig. 77, it measures the power delivered to the circuit CC plus the power consumed in heating the circuit *ar*; hence the wattmeter reading is greater than the power delivered to the circuit CC.

Again, if a wattmeter is connected as shown in Fig. 78, it measures the power delivered to the circuit CC plus the power consumed in heating the coil *b*; hence, in this case also, the wattmeter reading is greater than the power delivered to the circuit CC.

The **compensated wattmeter** of the Weston Electrical Instrument Company is designed to eliminate the above-mentioned sources of error. In this wattmeter the connections are as shown in Fig. 77.

Let C be the current in CC, and let a be the current in a and r. Then the current in b is C + a, and the force action upon the movable coil is proportional to the product a (C + a), instead of being proportional to the product aC. In the compensated wattmeter, the wire leading over to the coil a, connected as shown, is laid alongside each and every turn of wire in coil *b*. Then current C + *a* flows down through *b*; current *a* flows back alongside the wire of coil *b*; and the result is the same as if the current *a* were subtracted from the current C + *a*, so far as the magnetic action of the coil *b* is concerned.

37. The **recording wattmeter** is an instrument for summing up the total work or energy expended in a circuit in a given time. The recording wattmeter, so called, does not measure watts but watt-hours or kilowatt-hours, and would more properly be called a watt-hour meter.

The **Thomson recording wattmeter** is a small electric motor without iron, the field and armature coils of which constitute an electrodynamometer.

The field coils BB of this motor, Fig. 79, are connected in series with the circuit CC, in which the work to be measured is expended. The armature A, together with an auxiliary non-inductive resistance R, is connected between the terminals of the circuit CC, as shown. Current is led into the armature by means of the brushes *dd* pressing on a small silver commutator *e*.

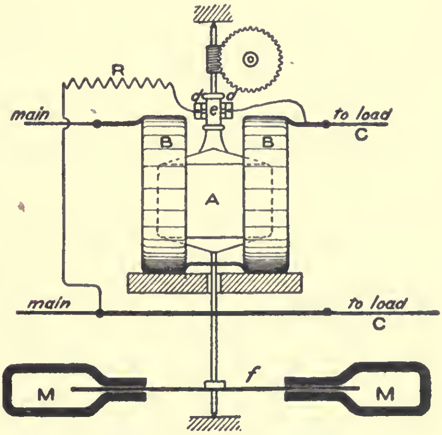


Fig. 79.

Discussion of the Thomson Recording Wattmeter.—The stationary and movable coils of the Thomson watt-hour meter are connected to the mains and receiving circuit (that is, to the load) exactly as are the stationary and movable coils of the indicating watt-meter; and the torque which the stationary (field) coils exert upon the movable coil (armature) is proportional to the watts delivered; that is, is proportional to the *rate* at which energy is being delivered to the receiving circuit.

The instrument is so constructed that the speed of its armature is proportional to the torque that drives it. Therefore the rate of turning of the armature is proportional to the rate at which energy is delivered to the circuit CC. Hence *the total number of revolutions turned by the armature in a given time is proportional to the total energy expended in the circuit* CC.

To make the armature speed proportional to the driving torque, the armature is mounted so as to be free, as nearly as possible, from ordinary friction; and a copper disc *f*, Fig. 79, is mounted on the armature spindle so as to rotate between the poles of permanent steel magnets MM. To drive such a disc requires a driving torque proportional to its speed.

The Starting Coil. In the above discussion it is assumed that the torque which opposes the motion of the armature A, Fig. 79, is proportional to the speed of the armature. In fact, however, this opposing torque may be considered as consisting of two parts: (1) the torque required to overcome friction ; and (2) the torque required to overcome the damping action of the magnets on the copper disc. The first part of the torque may be taken to be approximately constant, while the second part is accurately proportional to the speed. Therefore an arrangement for exerting on the armature a constant torque, sufficient to overcome friction, would largely eliminate errors due to friction. This is accomplished in the Thomson meter by supplementing the field coils B. Fig. 79, with an auxiliary field coil *connected in the armature circuit.* This auxiliary field coil is called a **starting coil.** So long as the electromotive force between the mains does not vary, the current in the starting coil is constant, and it therefore exerts a constant torque upon the armature. If, however, the electromotive force between the mains varies, the torque, due to the starting coil, varies with the square of the electromotive force.

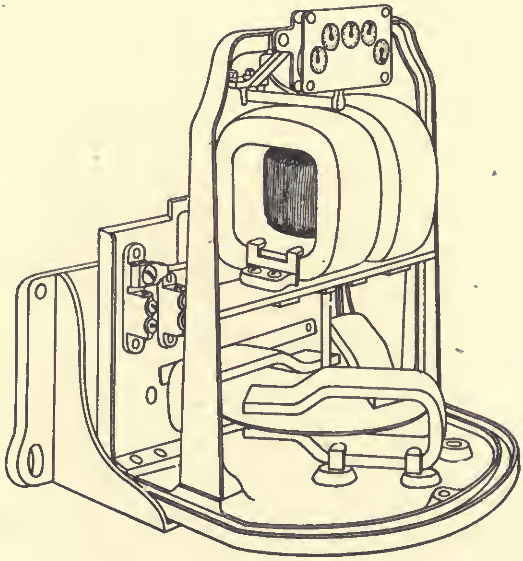


Fig. 80.

Example. A certain recording wattmeter will not run, even if started by a slight impulse from the hand, until the delivered power reaches 37.5 watts; that is, the running friction of the wattmeter is equal to the driving torque produced by 37.5 watts of delivered power. This wattmeter is adjusted (by moving the damping magnets) so as to read correctly when the delivered power is 500 watts. What will the instrument indicate when run for four hours with constant delivery of 200 watts of power?

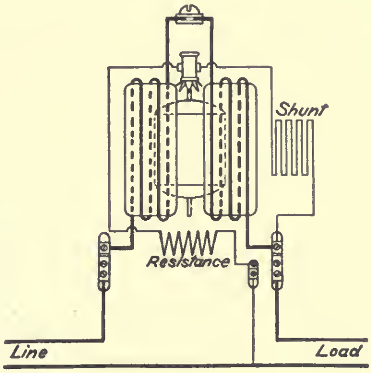


Fig. 81.

Let us express *driving torque* in terms of *watts of power delivered* to the receiving circuit, since the driving torque is proportional to the watts delivered. Let us express *speed* in terms of *watt-hours indicated* by the dials per hour. Now, the speed is proportional to that part of the driving torque which is used to overcome the retarding action of the damping magnets. In the problem under consideration, the total driving torques are 500 watts and 200 watts respectively; and since the running friction absorbs 37½ watts of torque, the torques available for overcoming the retarding action of the damping magnets are respectively (500 − 37½) watts and (200 − 37½) watts. The speed in the first case is 500 watt-hours per hour. Let x be the speed (watt-hours indicated per hour) in the second case. Then

$$(500 - 37\tfrac{1}{2}) : (200 - 37\tfrac{1}{2}) :: 500 : x$$

This gives a value of 175.6 watt-hours per hour for x, so that the watt-hours recorded in four hours run will be 4 × 175.6 watt-hours per hour, or 702.4 watt-hours. The actual total of watt-hours delivered is of course 4 hours × 200 watts, or 800 watt-hours.

The effect of running friction in a recording wattmeter is to cause the instrument to read low for an amount of delivered power that is less than the delivered power for which the damping magnets are adjusted to give a correct reading.

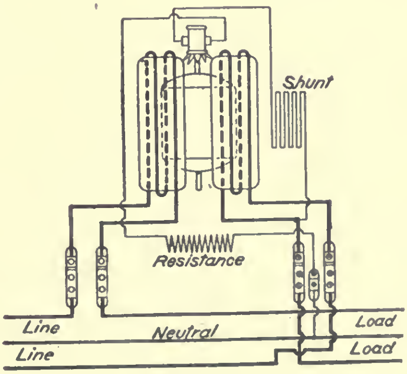


Fig. 82.

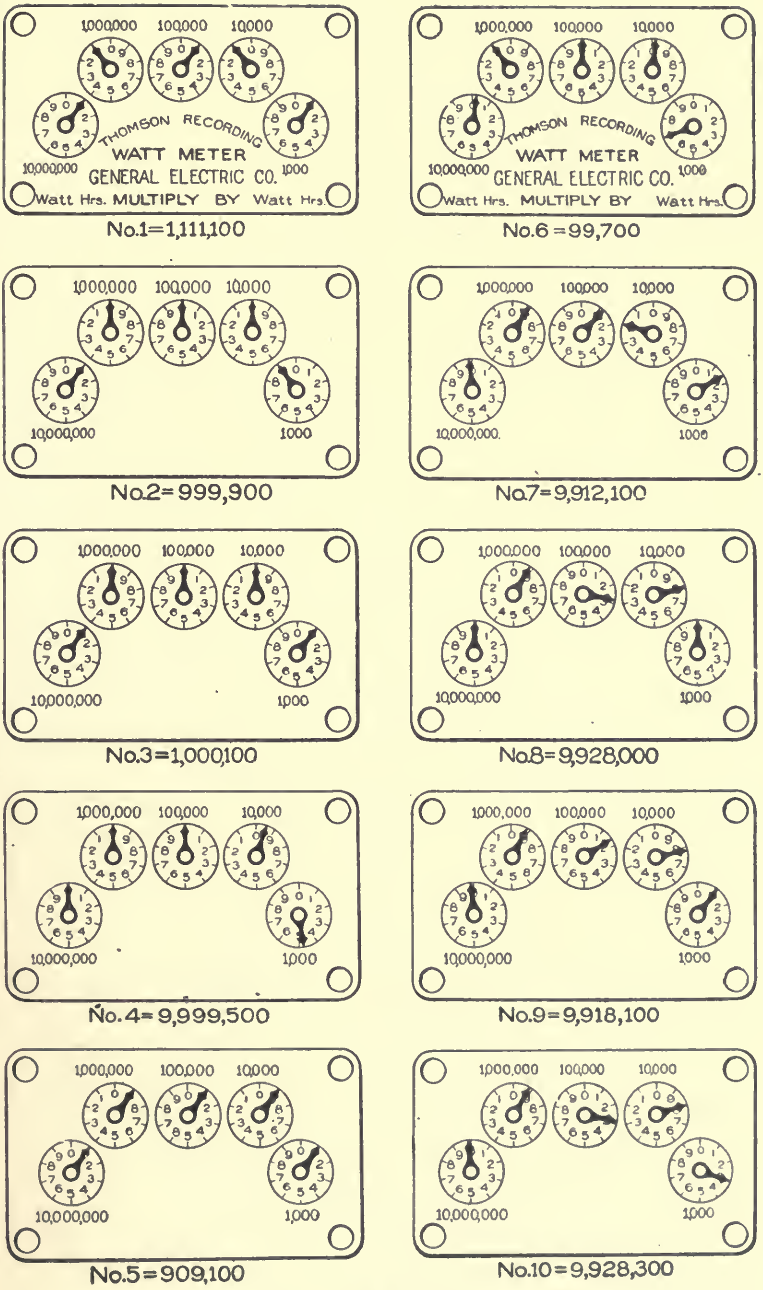
Fig. 80 shows a general view of a Thomson recording wattmeter (watt-hour meter). Fig. 81 shows the connections of a

Thomson recording wattmeter to two-wire supply mains (single-phase); and Fig. 82 shows the connections of a Thomson recording wattmeter to three-wire supply mains (single-phase.)

Directions for Reading Recording Wattmeter Dials. To read correctly the dial of a recording meter, some care is necessary. The figures marked under or over a dial (1,000, 10,000, etc.), are the amounts recorded by a complete revolution of the hand, therefore, one division on a dial indicates one-tenth of the amount indicated above or below. A complete revolution of the first hand (the one to the extreme right) in diagram No. 6, Fig. 83, for example, indicates 1,000, and moves the second hand one division of the second dial. The first hand, in the position given it in the diagram, indicates 700—not 7,000.

In deciding on the reading of a hand, the hand before it (to the right) must be consulted. Unless the hand before it has reached or passed the 0, or, in other words, completed a revolution, the other has not completed the division on which it may appear to rest. For this reason, ease and rapidity are gained by reading a meter from right to left. For example, in Diagram No. 2, the first dial (the extreme right) reads 900. The second apparently indicates 0; but, since the first has not completed its revolution, but indicates only 9, the second cannot have completed its division; hence the second dial also indicates 9. The same is true of the hand of the third dial; the second, being 9, has not quite completed its revolution; so the third has not completed its division, and therefore we again have 9. The same holds true of the hand of the fourth dial. The last hand (the extreme left) appears to rest on 1; but since the fourth is only 9, the last has not completed its division and therefore indicates 0. Putting the figures down from right to left, the total reading is 999,900, though one might erroneously read 1,999,900, making a mistake of 1,000,000 units.

The hands sometimes become slightly misplaced, as shown in diagrams Nos 8, 9 and 10. In No. 8 we have on the first dial (the extreme right) 0; we therefore put down three zeros, thus: 000. The hand of the second dial is misplaced; for inasmuch as the first registers 0, the second should rest exactly on a division; therefore we know that it should have reached 8, making 8,000. The remaining hands are correct, and make a total of 9,928,000.



No.1=1,111,100

No.6=99,700

No.2=999,900

No.7=9,912,100

No.3=1,000,100

No.8=9,928,000

No.4=9,999,500

No.9=9,918,100

No.5=909,100

No.10=9,928,300

Fig. 83.

In diagram No. 9 the second hand is misplaced; for since the first indicates 1, the second should have just passed a division, and, as it is nearest to the 8, we know it should have just passed that figure. The remaining three hands are approximately correct. The total reading is 9,918,100.

In diagram No. 10 the second hand is behind its correct position. The total indication is 9,928,300.

By carefully following these directions one will find little difficulty in reading a meter even if the hands become misplaced

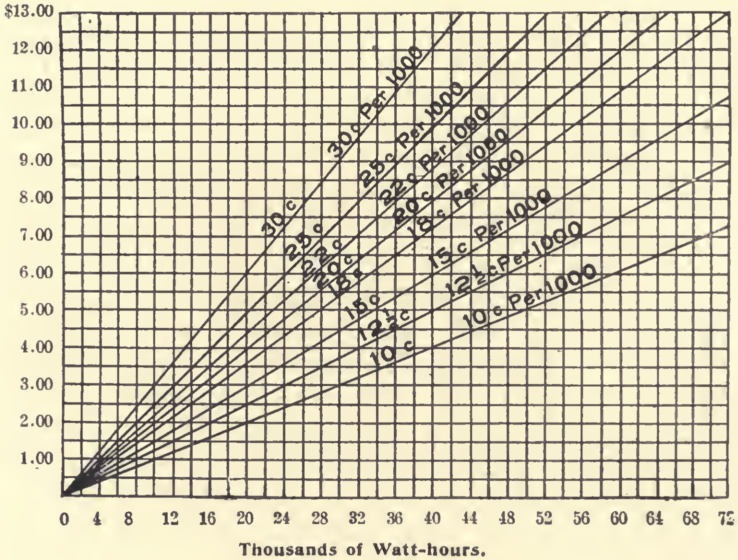


Fig. 84.

The above directions apply to recording wattmeters of all kinds—induction wattmeters as well as Thomson wattmeters.

Calculations of Customers' Bills. The consumption of energy in watt-hours being known, the exact amount of the bill can at once be read from a **price chart,** one of which is shown in Fig. 84. Dollars and cents are read from the vertical line at the left, while the horizontal line at the bottom of the chart indicates thousands of watt-hours. To determine the amount to be charged for say 26,000 watt-hours at 25 cents per 1,000 watt-hours, follow the vertical line marked 26 to its intersection with the diagonal line marked 25 cents. From the intersection of these two lines, follow the horizontal line to the left, and find $6.50, which is the amount of the bill for 26,000 watt-hours at 25 cents per 1,000 watt-hours.

ALTERNATORS.

38 a. The fundamental Equation of the Alternator. The equation expressing the effective electromotive force of an alternator in terms of the useful magnetic flux per pole, the number of poles, the number of armature conductors, and the speed of the armature, is called, from its importance in calculations in designing, the "fundamental equation of the alternator." This equation is

$$E = \frac{Kp\Phi nZ}{10^8} \text{ volts}, \qquad \textbf{(29}a\textbf{)}$$

in which

E is the effective electromotive force of the alternator;

K is what we shall call the electromotive force factor of the machine:

p is the number of poles of the field magnet;

Φ is the useful magnetic flux per pole, that is, the number of lines of magnetic flux that cross the gap from one pole into the armature;

n is the speed of the armature in revolutions per second; and

Z is the total number of conductors on the surface of the armature.

The value of K depends upon the ratio of breadth of pole face to pole pitch, and upon the distribution of windings upon the armature core.

DISCUSSION OF EQUATION **29**a. We shall discuss this equation for the simplest case only, that is, when the armature conductors are concentrated in one slot per pole. This type of winding is called a **concentrated** or **uni-coil winding**, as shown in part in Fig. 85.

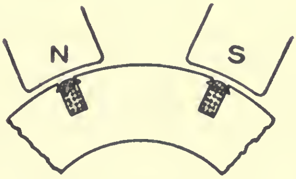


Fig. 85.

A given conductor cuts $p\Phi$ lines of force in passing all of the poles in one revolution; and since the armature makes n revolutions per second, the given conductor cuts $np\Phi$ lines of force per second. Now, by definition, the cutting of one line of force per second induces in a conductor one *c.g.s.* (centimeter-gram-second) unit of electromotive force. Therefore there is an average of $np\Phi$ *c.g.s.* units of electromotive force induced in one armature conductor; but since there are Z armature conductors in series between the collector rings, the average electromotive force between collector rings is

$$Znp\Phi \text{ } c.g.s. \text{ units}$$

or

$$\frac{Znp\Phi}{10^8} \text{ volts.}$$

The factor by which the average electromotive force must be multiplied to give the effective electromotive force is called the "form factor of the electromotive force curve of the alternator." Therefore, if K is this form factor, we have:

$$\text{Effective E} = \frac{KZnp\Phi}{10^8} \text{ volts.}$$

This equation may be written so as to give the electromotive force (effective) of the alternator in terms of the number of turns T of wire on the armature, and of the frequency f, as follows:

Since

$$\frac{Z}{2} = T, \text{ or } Z = 2T,$$

and

$$pn = 2f,$$

therefore, substituting these values of pn and Z in equation 29*a*, we have:

$$E = \frac{4K\Phi fT}{10^8} \text{ volts.} \qquad (29^b)$$

Example. An alternator has 200 turns of wire on its armature, and 1,000,000 lines of magnetic flux from each field pole. It is run to give a frequency of 125 cycles per second. The value of the factor K is 1.11 (sine-wave electromotive force curve and concentrated winding). The effective electromotive force of this alternator, therefore, is:

$$\frac{4 \times 1.11 \times 10^6 \times 125 \times 200}{10^8} = 1{,}110 \text{ volts.}$$

38 b. The Electromotive Force Factor K in Equation 29*a*. When the magnetic flux is distributed in the ideal way explained below and represented in Fig. 86, the factor K is called the **phase constant** of the winding.

When the winding is concentrated, the factor K is called the **form factor** of the electromotive force curve. This factor K depends in general upon the manner in which the magnetic flux is distributed in the air gap, and upon the manner in which the armature windings are distributed around the armature.

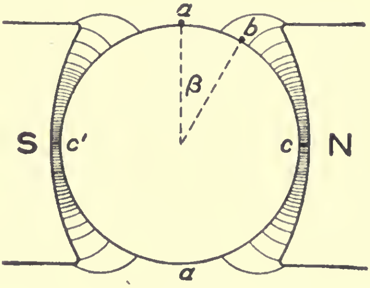


Fig. 86.

Case 1. *When a Harmonic Electromotive Force is Induced in Each Turn of the Armature Winding.* This is the case—never fully realized in practice—when the magnetic flux-density (that is, the field intensity in the gap space between the pole faces and the iron of the armature core) is zero at the points a, Fig. 86, and when this field intensity increases to a maximum at c and at c' in such a manner that the field intensity at any point b is proportional to the sine of the angle β.

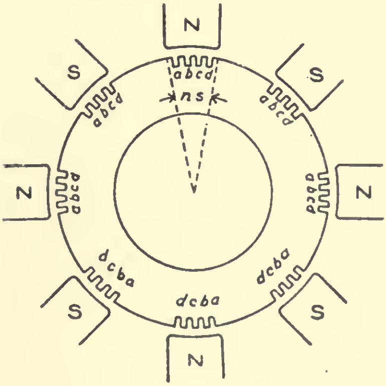


Fig. 87.

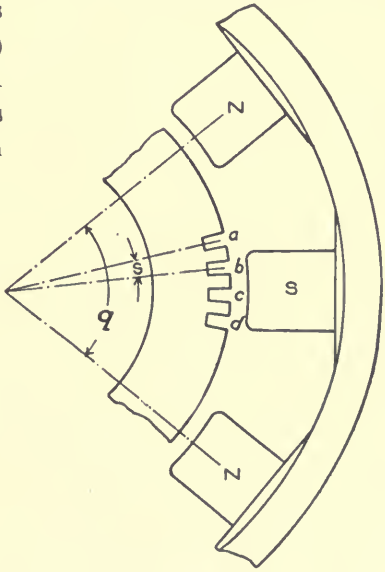


Fig. 88.

Consider an armature rotating in a field distributed in the ideal way above specified. Suppose the winding to be arranged in slots spaced as shown in Fig. 87, four slots per pole. Fig. 88 shows one group *a b c d* of these slots drawn to a larger scale. Two wires on the armature, at a distance apart equal to the distance between adjacent north poles, and subtending the angle q, Fig. 88, have induced in them two electromotive forces. These forces are to be thought of as differing in phase by 360°, because of the fact that the electromotive force in a given conductor passes through a complete cycle while the conductor moves from the center of a given north pole to the center of the next north pole. Therefore the phase difference of the electromotive forces induced in the wires placed in slot a, and those induced in the wires placed in slot b, is $\frac{s}{q} \times 360°$; or, in other words, this angle is:

$$\frac{\text{width of tooth} + \text{width of slot}}{\text{circumference of armature} \div \text{number of pairs of poles}} \times 360°.$$

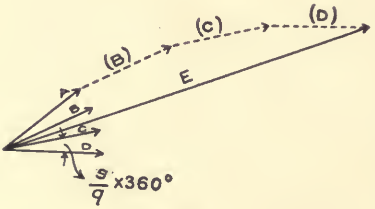


Fig. 89.

The lines A and B in the clock diagram, Fig. 89, represent in magnitude and phase the electromotive forces induced in the wires in slots a, Fig. 87, and in the wires in slots b, Fig, 87, respectively. Similarly, the lines C and D in Fig. 89 represent the electromotive forces induced in the wires in slots c, Fig. 87, and in the wires in slots d, Fig. 87, respectively. If, now, the windings in the slots a, b, c, and d, Fig. 87, are connected in series, the total electromotive force produced by all the windings will be represented by the line E in Fig. 89. The line E is the closing side of the polygon of which the sides (A), (B), (C), and (D) are drawn respectively parallel and equal to the electromotive force lines A, B, C, and D. The value of K, which, in the case of the ideally distributed field flux here considered, is called the "phase constant" of the winding, is equal to the ratio

$\frac{E}{4A}$; that is, the value of K is equal to the ratio of the length of the line E to four times the length of one of the lines A, B, C, or D

Case 2. *When a Harmonic Electromotive Force is Not Induced in Each Turn of the Armature Winding.* We shall discuss, first, the case of a *concentrated* winding (in which case K is simply the "form factor" of the electromotive force wave); and then the case of a *distributed* winding.

Fig. 90 shows a developed view of a four-pole alternator having four armature conductors *a*, *b*, *c*, and *d*. Of course, these four conductors are connected in series between the collecting rings (not shown in the figure); and in tracing the circuit from one collecting ring to the other, one would pass down along conductor *a*, then across to conductor *b*, up *b*, then across to conductor *c*, down *c* then across to conductor *d*, up *d*, and then to the other collecting ring. The directions of the electromotive forces induced in the various conductors are indicated thus ⊙ and ⊕. The symbol ⊙ indicates an electromotive force directed *towards* the reader, and the symbol ⊕ indicates an electromotive force directed *away from* the reader.

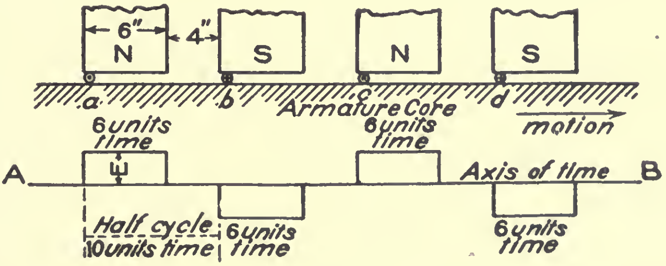


Fig. 90.

Let us reckon time from the instant when conductor *a* is in the position shown; and let time be plotted as abscissas, and successive values of the induced electromotive force as ordinates, in the diagram AB, Fig. 90. Suppose that the intensity of the field in the gap space between pole faces and armature core is uniform, and that it terminates sharply at the pole tips, that is, that there is no spreading of the lines of force such as is shown in Fig. 11 (Part I). As a matter of fact, however, the field always does spread. The armature conductors move with uniform velocity to the right, and the ratio of breadth of pole face (6 inches) to pole pitch (10 inches) is $\frac{6}{10}$.

Then, during each cycle of which the duration is 20 units of time, the successive instantaneous values of the induced electromotive force are:—constant, positive, and equal to E for 6 units of time; they are zero for 4 units of time; they are constant, negative, and equal to E for 6 units of time; and they are again zero for 4 units of time. The *average value* of the electromotive force during the first half cycle is therefore equal to

$$\frac{E \times 6 + 0 \times 4}{10} = \frac{6}{10} E \text{ volts.}$$

The squares of the successive instantaneous values of the induced electromotive force are:—constant, positive, and equal to E^2 for 6 units of time; they are then zero for 4 units of time; and so on. The *average value of the squares* of the successive instantaneous values of the induced electromotive force during half a cycle is therefore equal to

$$\frac{E^2 \times 6 + 0^2 \times 4}{10} \text{ volts}^2 = \frac{6}{10} E^2 \text{ volts}^2,$$

from which we find the effective value by extracting the square root. Thus,

$$\text{Effective value of induced electromotive force} = \sqrt{\frac{6}{10}} \times E \text{ volts.}$$

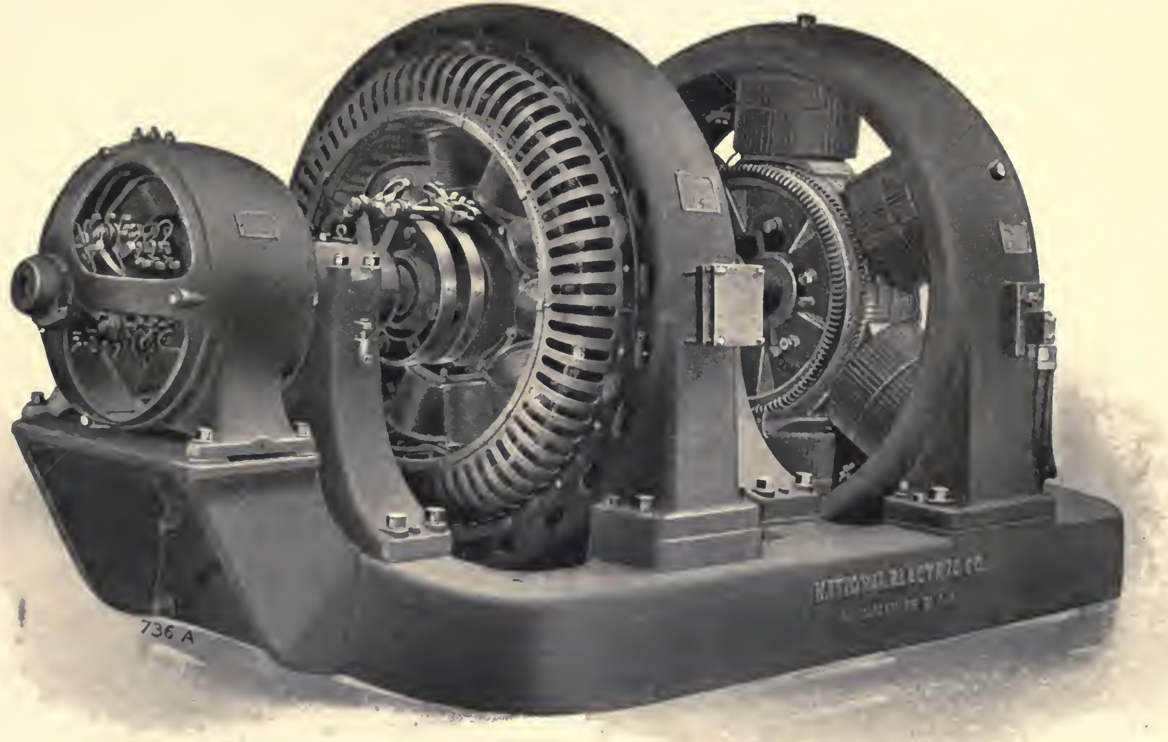
The value of K (form factor), in the case of a *concentrated* winding, is

$$K = \frac{\text{effective value}}{\text{average value}} = \frac{\sqrt{\frac{6}{10}}\,E}{\frac{6}{10}\,E} = 1.29.$$

The value of K for a concentrated winding may be calculated, as in the above example, for any breadth of pole face.

The value of K, in the case of a *distributed* winding, is calculated as follows:

Fig. 91 shows a four-pole alternator with two armature conductors *a* and *b* for each field pole. (Only two of these conductors



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are shown in the figure). The curve of the electromotive force induced in all the *a* conductors is shown by the rectangular waves AB. This electromotive force has a constant, positive value E for 12 units of time ; then a zero value for 8 units of time ; then a constant, negative value E for 12 units of time ; and so on.

The curve of the electromotive force induced in all the *b* conductors is shown by the rectangular waves CD. This electromotive force rises from zero to the full value E at the instant when the conductors *b* are in the position of *a*, as shown in the figure ; that is, the electromotive force induced in conductors *b* rises from zero to its full value E, 7 units of time before the corresponding rise of the electromotive force in conductors *a*.

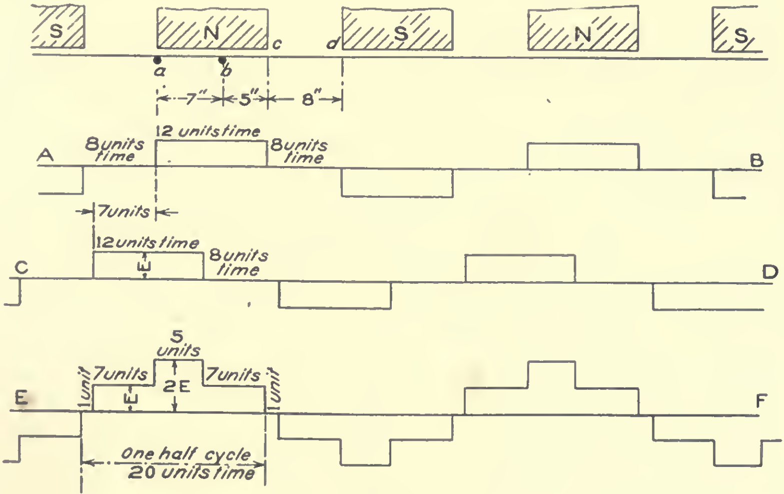

Fig. 91.

The total electromotive force curve EF, Fig. 91, of the alternator, is found by adding corresponding ordinates of the curves AB and CD. A careful inspection and comparison of AB and CD shows that the total electromotive force of the alternator is zero for 1 unit of time, equal to E for 7 units of time, equal to 2E for 5 units of time, and equal to E for 7 units of time, during each half cycle of 20 units of time. Therefore the average value of the electromotive force EF during half a cycle, is:

$$\frac{0 \times 1 + E \times 7 + 2E \times 5 + E \times 7}{20} = \frac{24}{20} \times E = 1.2E.$$

Referring to the curve EF, Fig. 91, it is evident that the squares of the successive instantaneous values of the total electromotive force of the machine are as follows: 0^2 for one unit of time, E^2 for seven units of time, $(2E)^2$ for five units of time, and E^2 for seven units of time, during each half cycle of twenty units of time. Therefore the average value of the squares of the electromotive force EF during half a cycle, is

$$\frac{(0^2 \times 1) + (E^2 \times 7) + (4E^2 \times 5) + (E^2 \times 7)}{20} = \frac{34}{20} \times E^2;$$

and the effective value of the electromotive force EF is:

$$\sqrt{\frac{34}{20}} \times E = 1.304E.$$

The value of K for the case under consideration, as shown in Fig. 91, is the ratio:

$$\frac{\text{effective electromotive force}}{\text{average electromotive force}} = \frac{1.304}{1.2} = 1.087,$$

which is simply the form factor of the electromotive force curve of the alternator.

NOTE.—The factor K is the same thing as form factor whenever the distance *ab*, Fig. 91, between the remotest conductors of a group of conductors is less than the distance *cd* between the pole tips, on the assumption that the magnetic lines of force do not spread into the spaces between the pole tips.

39. Armature Reaction. The current that circulates in an alternator armature has magnetizing action; and the actual useful flux Φ per pole is due to the combined magnetizing action of the field coils and of the armature coils. This magnetizing action of the armature current in its effect upon the useful flux Φ, is called "armature reaction." In case the current in the armature *lags behind* the electromotive force (when, for example, the outside receiving circuit has inductance, as when the alternator supplies current to induction motors), the effect of armature reaction is to *reduce* the useful flux Φ from each pole. In case the current in the armature *is ahead of* the electromotive force in phase (a condition that sometimes obtains when the alternator supplies current to a synchronous motor or to any receiving apparatus over a long transmission line, or, in general, when the receiving apparatus acts like a condenser), the effect of armature reaction is to *increase* the useful flux Φ from each pole.

To state the matter in another way, it may be said that the effect of a lagging armature current is to oppose the magnetizing action of the field coils. On the other hand, the effect of a leading current in the armature is to help the magnetizing action of the field coils.

In an alternator the invisible variations in phase difference between the armature current and the electromotive force, due to the varying character of the receiving apparatus, correspond, in their influence on armature reaction, to the visible variations in the position of the brushes of a direct-current generator.

Fig. 92 represents a single-phase alternator running in the direction indicated by the curved arrow. The electromotive force induced in the armature coil A is zero at the instant when the armature is in the position shown; and if the armature current is in phase with the electromotive force, the current also will be zero at this instant.

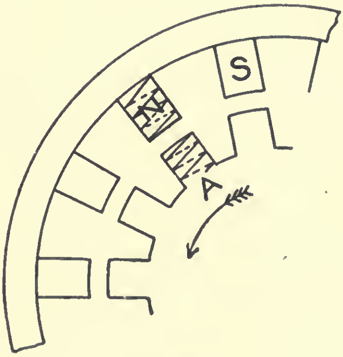

Fig. 92.

In considering armature reaction we shall discuss three cases, as follows:

1. Armature current in phase with electromotive force.
2. Armature current lagging behind electromotive force.
3. Armature current leading the electromotive force.

CASE 1. As the armature tooth A, Fig. 92, passes by the field pole N, the current in the armature coil on A is reversed in direction. If the current is in phase with the electromotive force induced in the armature, this reversal of direction of current occurs at the instant when the tooth A is squarely under N. In this case the armature current flowing in coil A just previous to the reversal (that is, when the tooth A is approaching N), opposes by its magnetizing action the flux from N; and after reversal the current in the coil A helps the flux from N. Therefore the former or demagnetizing action of coil A is balanced by the subsequent magnetizing action ; and the only effect of the armature current in A is to weaken the one side of the pole N, and to strengthen to an equal extent the other side, thus leaving the useful flux Φ unchanged.

Case 2. When the current lags behind the electromotive force, the reversal of current in the coil A occurs at a later instant than in Case 1, that is, when the coil A has passed beyond the center of the pole N. Hence the demagnetizing action of the current in coil A before reversal lasts for a longer time than the magnetizing action of the current in coil A after reversal, and the demagnetizing action exceeds the magnetizing action. Therefore the resultant effect of the armature reaction is to decrease the useful flux Φ from the pole N.

Case 3. When the current is in advance of the electromotive force in phase, the reversal of current in the coil A occurs at an instant earlier than in Case 1, that is, before the coil A has reached the center of the pole N. Hence the demagnetizing action of the current in coil A before reversal lasts for a shorter time than the magnetizing action of the current in coil A after reversal, and the magnetizing action exceeds the demagnetizing action. Therefore the resultant effect of the armature reaction is to increase the useful flux Φ from the pole N.

40. Armature Inductance. The value of the inductance of an alternator armature varies with the position of the armature coils with respect to the field magnet poles, so that the inductance of an armature increases and decreases at a frequency twice* as great as the frequency of the electromotive force of the alternator. The armature of the alternator shown in Fig. 1 (Part 1), for example, has about three or four times as much inductance when the armature teeth are squarely under the field poles as it has when the armature teeth are midway between field poles. That is, the flux produced through the armature teeth by a given current is three or four times as great in the first case as in the second case. This fluctuation of armature inductance makes it very difficult to predetermine the electromotive force, and, in general, the behavior of a machine. In the following discussion the armature inductance is assumed to be constant.

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* The electromotive force of an alternator passes through a cycle when an armature coil passes from a north pole of the field to the next north pole. The inductance passes through a cycle of values when an armature coil passes from one field pole to the next field pole.

The inductance of an alternator armature is proportional to the linear dimensions of the armature, other things being equal; and the inductance of an armature of given size is much greater when the winding is concentrated than it is when the winding is distributed.

A moderate amount of armature inductance is advantageous in alternators which are to be run in parallel; and in case of a short circuit, the armature inductance keeps the current from becoming excessive. Armature inductance is more or less objectionable in an alternator which is to be used to supply current at constant electromotive force, on account of the electromotive force that is lost in the armature, as explained in the next article.

The inductance of an armature is best determined by sending through it when at rest, from an outside source, a measured alternating current I, and measuring the electromotive force E between the collecting rings. Then

$$E = I\sqrt{R^2 + \omega^2 L^2}$$

or, solving for L, we have:

$$L = \frac{1}{I\omega}\sqrt{E^2 - (IR)^2} \qquad (30)$$

Knowing the armature resistance and the frequency $\frac{\omega}{2\pi}$, we can find L from equation 30. The value of L depends greatly upon the position in which the armature is held, as explained above, and upon the degree of field excitation.

Example. The armature of a single-phase alternator has a resistance of 0.2 ohm. An electromotive force of 100 volts at a frequency of 125 cycles per second ($\omega = 785$ radians per second) applied to the collecting rings of the armature at rest, produces an effective current of 100 amperes. Therefore the inductance of the armature, as calculated by use of equation 30, is 0.00125 henry.

41. Electromotive Force Lost in Armature Drop. The electromotive force between the collecting rings of an alternator with given load, is less than the electromotive force between rings at zero load, with given field excitation, because of two electromotive force losses that occur, and because of the effect of armature reaction.

(*a*) The loss of electromotive force, or the drop, is due, in the first place, to the resistance of the armature. This loss is equal to RI; it is in phase with I; and it is precisely analogous to the electromotive force lost in a direct-current armature due to the resistance of the armature.

(*b*) The loss of electromotive force, or the drop, is due, secondly, to the inductance of the armature. This loss is equal to ω LI, and it is 90° ahead of I in phase.

(*c*) The demagnetizing action of the armature current on the field lessens the useful flux, and thus indirectly causes a falling-off in the induced electromotive force.

The result of the actions *b* and *c* above is to cause a loss of electromotive force in the armature of the same character in each case in so far as phase relations with current are concerned. Therefore it is convenient to attribute the total effect of *b* and *c* to a fictitious armature inductance L′, which is, of course, larger in value than the armature inductance L in equation 30. The inductance reactance ω L′ corresponding to this equivalent inductance L′, is called the **synchronous reactance** of the armature.

An example of the calculation of synchronous reactance is given later on, in the articles on Alternator Losses, Efficiencies, etc.

42. Alternator Regulation. Given an alternator, having constant field excitation. It has a certain electromotive force between collecting rings when its current output is zero. As the current output increases, the electromotive force between collector rings generally decreases, because of the actions described in the foregoing article; and, conversely, as the current output decreases, the terminal electromotive force rises. The *increase* of electromotive force from full load to zero load, with constant full-load field excitation, expressed as a percentage of the full-load terminal electromotive force, is called the **regulation** of the alternator.

Example. A certain alternator gives 1,100 volts between its collector rings at full-load current and full-load field excitation. When the current output is decreased to zero by opening the main switch, leaving the field excitation and speed unchanged, the terminal electromotive force rises to 1,166 volts. The regulation, according to the above definition, is:

$$\frac{1,166 - 1,100}{1,100} \times 100 = 6 \text{ per cent.}$$

The regulation of a given alternator varies greatly with the character of the receiving circuit to which it delivers current. When the receiving circuit has large inductance reactance (as in the case of under-loaded transformers and induction motors), the terminal electromotive force, under increasing load, falls off very much more than when the receiving circuit is non-inductive (as, for example, when the receiving circuit consists of incandescent lamps supplied through fully loaded transformers). In other words, the regulation of an alternator is larger for inductive receiving circuits than for non-inductive receiving circuits. If the receiving circuit has large capacity reactance (as, for example, when the receiving circuit consists of over-excited synchronous motors), the terminal electromotive force of the alternator will rise with an increase of the current output; and the regulation of the alternator, according to the above definition, will be negative. In practice, the receiving circuit never as a whole has capacity reactance.

Example. A given alternator has a regulation of 8 per cent on a non-inductive receiving circuit (unity power factor), and one of 15 per cent on an inductive receiving circuit having a power factor of 0.8.

43. Field Excitation. In most alternating-current systems the voltage at the points from which current is distributed is kept constant or approximately constant. This requires that the voltage at the terminals of the alternator be somewhat increased as the amount of current (or load) is increased, the amount of the increase in electromotive force depending on the volts lost in the line. If the field excitation of an alternator be kept constant while the current taken from the armature is increased, the voltage at the terminals will decrease, just as in the case of a direct-current shunt dynamo. Hence, in order to keep the voltage at the terminals constant, or to cause a rise of voltage with increasing current output, it becomes necessary to increase the field excitation with increasing current output.

There are in general three methods in use for accomplishing this regulation:

1. By adjustable rheostat in alternator field circuit, or in exciter field circuit, or in both.
2. By composite field winding, which is a combination of self and separate field excitation.
3. By compensated field winding.

Case 1. *Separate Excitation.* The simplest method is that illustrated by the diagram, Fig. 93, in which A represents the armature winding, the terminals of which, T_1, T_2, are connected to the collector rings, which in turn are connected to the line wires through the brushes.

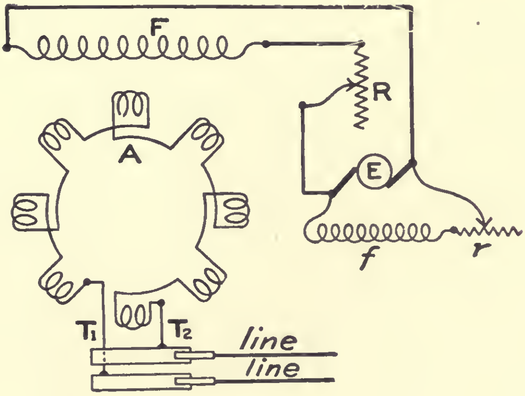

Fig. 93.

The field of the alternator is excited by a set of coils on the pole pieces. These coils are represented by F; and current is supplied to these coils from a small direct-current dynamo, E, called the "exciter." This exciter is a small shunt-wound dynamo furnished with an adjustable rheostat r in series with its field f. An adjustable rheostat R is placed in the alternator field circuit also. When the electromotive force of the alternator decreases, the field may be strengthened by cutting out resistance in either R or r, or in both.

Regulation by r alone is generally used in large machines, since the exciter's field current is relatively small, while the alternator field current is usually large and hence would cause a large $I^2 R$ loss if passed through a rheostat.

Case 2. *Composite Excitation.* The electromotive force of an alternator excited as in Case 1 falls off greatly with increasing current output; and to counteract this tendency automatically, an auxiliary field excitation is frequently provided, which increases with the current output of the machine. For this purpose the whole or a portion of the current given out by the machine is rectified,* and sent through the auxiliary field coils. This arrangement is shown in Fig. 94.

The field winding of the alternator has two sets of coils F and C. The coils F are separately excited as in Case 1. The coils C, known as the "series" or "composite coils," are excited by the main current from the alternator. One terminal of the armature winding is connected directly to a collecting ring. The other armature terminal connects to one set of alternate bars of the rectifying commutator B. From the rectifier the current is led through the winding C, thence back to the rectifier, and thence to the other collecting ring. The shunt *S*, within the commutator, may be used when it is desired to rectify only a part of the current. There is also a shunt *S'* which may be used to regulate the amount of current flowing through the coil C.

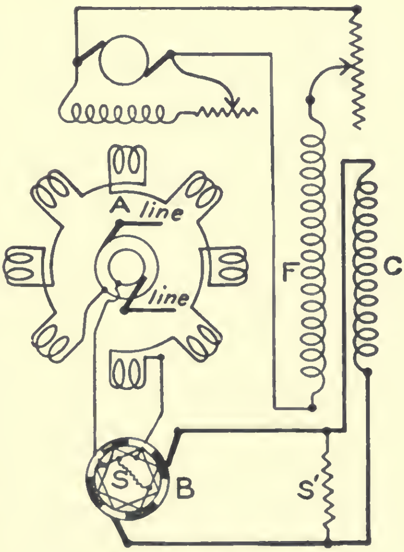

Fig. 94.

The alternating-current rectifier is an arrangement for reversing the connections of the field circuit with each reversal of the current from the alternator, so that the current may flow always in the same direction in the field circuit. The rectifier is a commutator mounted on the armature shaft. This commutator has as many bars as there are poles on the field magnet of the alternator. These bars are wide, and are separated by quite narrow spaces filled with mica. Let these bars be numbered in order around the commutator. The even-numbered bars are connected together, and the odd-numbered bars are connected together. The connecting wire leading from one terminal of the alternator armature to one of the collector rings is cut; and the two ends thus formed are connected, one to the even-numbered bars (shown in full black in Fig. 94) of the rectifying commutator, and the other to the odd-numbered bars (shown white in Fig. 94). The field circuit that is to receive the rectified current is connected to two brushes which rub on the rectifying commutator, these brushes being so spaced that one touches an odd-numbered bar when the other touches an even-numbered bar. The brushes are carried in a rocker arm, which is moved forwards or backwards until the brushes are passing from one bar to the next at the instant that the alternating current from the alternator is passing through the value zero. The proper adjustment of the brushes is indicated by a minimum of sparking.

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*Note.—Connections to field coils are reversed with every reversal of main current, so that, in the field coils, the current is uni-directional.

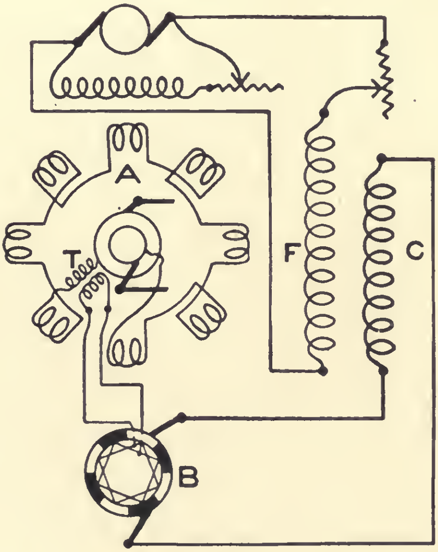

Fig. 95.

Fig. 95 shows an alternator A with two sets of field coils F and C as before. One armature terminal is connected to a collecting ring; and the other armature terminal connects to the primary of a transformer T, and thence to the other collecting ring. The terminals of the secondary coil of T connect to the bars of the rectifying commutator B, from which the composite field winding C is supplied. The transformer T is usually placed inside the armature.

Arrangement of Composite Field in Case of Two-phase and Three-phase Alternators. Composite field excitation is not satisfactory in case of polyphase alternators, unless the receiving circuits supplied from the alternators are approximately balanced. Unbalancing of the receiving circuits changes the electromotive forces generated in the different phases of the armature, by different amounts; and composite excitation cannot, of course, correct the electromotive force variations of all the phases.

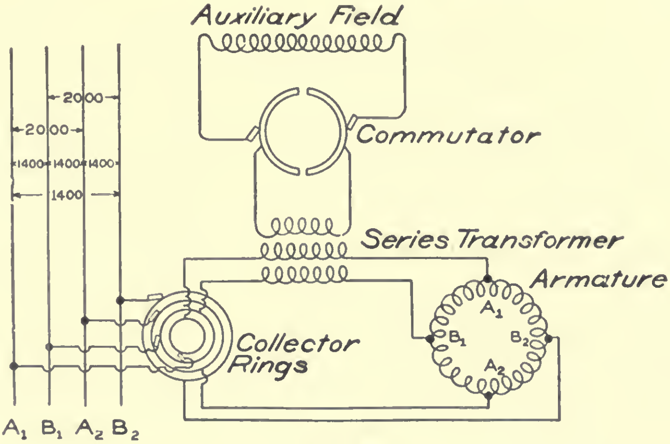

Fig. 96.

In case of approximate balance, the current for the composite field excitation is taken through a rectifying commutator from the secondary coil of a series (or current) transformer which has two

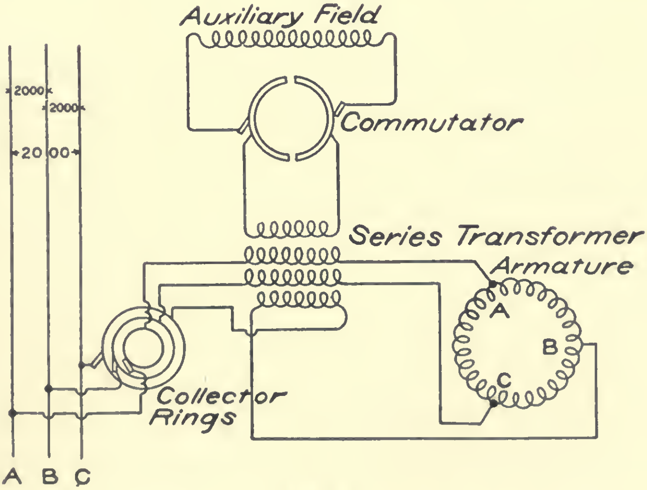

Fig. 97.

or three distinct primary coils, one for each phase. This arrangement is shown in Figs. 96 and 97. The effect of the several primary coils on the series transformer is to balance up the slight differences of the several polyphase currents, in so far as their action upon the composite excitation is concerned. This method is used by the Westinghouse Company.

CASE 3. *Compensated Excitation.* An alternator with composite excitation can be adjusted so that the terminal electromotive force between the collector rings can be kept fairly constant if the power factor of the receiving circuit is invariable. Variations of the power factor of the external circuit, *even though the current output of the machine remains constant in value*, produce variations of the terminal electromotive force of an alternator. These variations of terminal electromotive force cannot, of course, be corrected by the use of composite excitation, inasmuch as they are independent of variations of current output.

In the compensated polyphase alternator of the General Electric Company, variations of voltage due to changes of both current output and power factor of the receiving circuit, are approximately compensated. The action of this alternator is as follows:

The armature current in an alternator is magnetizing or demagnetizing in its effect on the alternator field according as it leads or follows the electromotive force of the generator. The amount of the magnetizing or demagnetizing action depends on the magnitude of the current and on the phase difference between the current and the electromotive force (*i. e.*, on the power factor of the receiving circuit). Under the usual conditions of practice, the current delivered by an alternator lags more or less behind the electromotive force, and thus exerts a demagnetizing action on the field of the alternator. This action causes the terminal electromotive force of the alternator to decrease, the amount of the decrease being larger the greater the current, and the greater the angle of the lag between the electromotive force and the current.

The alternating current delivered by the alternator may be passed, in whole or in part, through the armature of a small auxiliary double-current* generator, which is driven in synchronism with the main alternator. The field magnet of this auxiliary generator may be turned into such a position that the main alternating current, though lagging with respect to the electromotive force of the main alternator, will be leading with respect to the electromotive force of the auxiliary generator. The angle by which the main current will lead the electromotive force of the auxiliary generator will be greater, the greater the angle of lag of this current behind the electromotive force of the main alternator; or, in other words, the smaller the power factor of the receiving circuit being supplied with current from the alternator.

Under these conditions the field magnet of the auxiliary generator is strengthened either by increase of current delivered through it by the main alternator, or by increase of the lag of the main alternator current behind its electromotive force, or by both things combined.

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*NOTE.—For further information concerning double-current generators see later discussion.

The auxiliary machine supplies current to magnetize the field of the main alternator, so that the field of the main alternator is strengthened either by increase of current delivered by the main alternator, or by increase of the angle of lag of the main alternator current behind its electromotive force, or by both.

Compensation for falling off of the voltage of the main generator due to the above two causes, singly or combined, is thus accomplished.

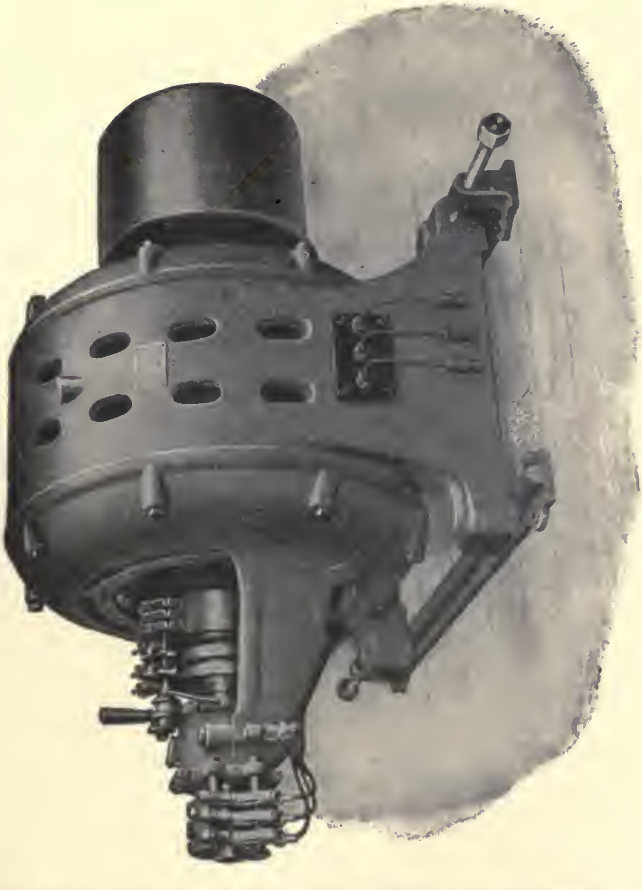

Fig. 98.

The above method for automatically controlling the voltage of alternators, as already said, is applied in the compensated field alternator, manufactured by the General Electric Company.

This machine consists of an ordinary multipolar polyphase (two-phase or three-phase) alternator, and a small multipolar (same

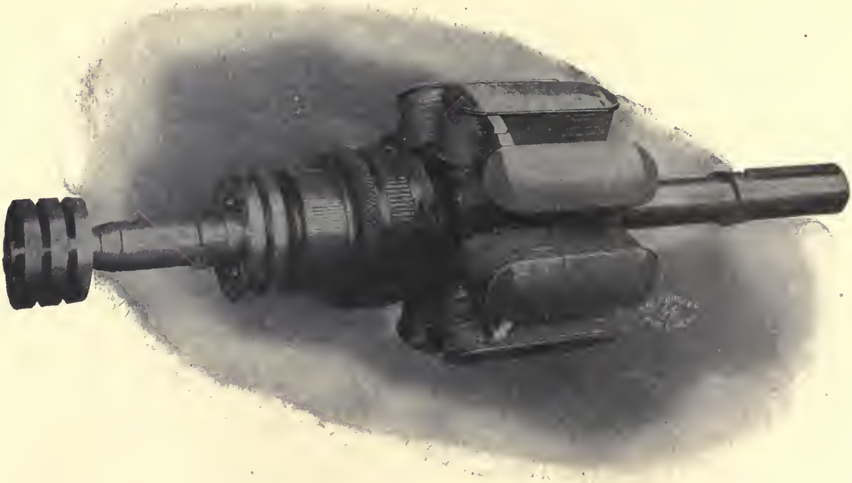

Fig. 99*a*.

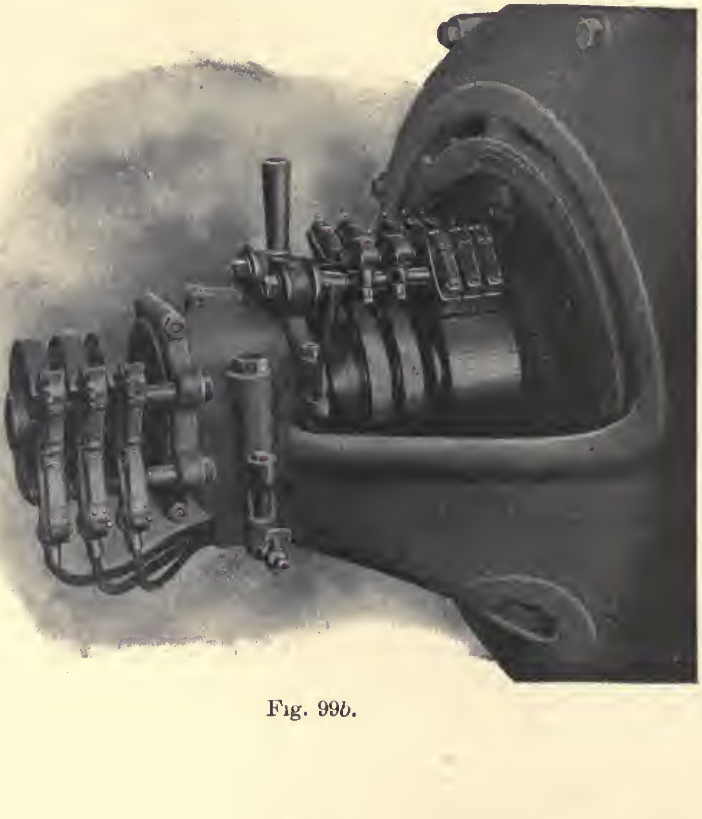

Fig. 99*b*.

number of poles as the main alternator) direct-current generator (the exciter). This exciter is provided with slip-rings as well as a commutator, and is thus a double-current generator.* It is driven on the same shaft with the main alternator.

When polyphase currents are delivered by the main alternator armature, they flow through the primaries of two (or three) transformers†; the secondaries of which are connected directly to the slip-rings of the exciter armature. In this way definite fractional parts of the main alternating currents flow through the exciter armature by way of the slip-rings, and strengthen the field of the exciter as above described.

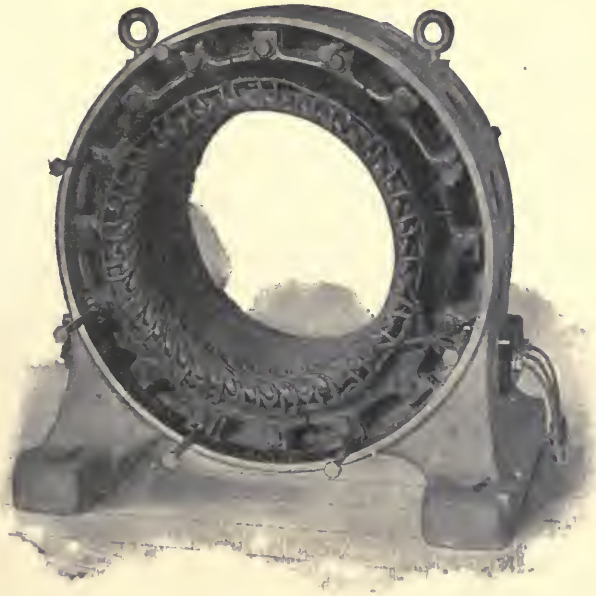

Fig. 99c.

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* For further information concerning double-current generators, see later discussion.

† A transformer connected so that the entire current output of an alternator must pass through its primary coil, gives a secondary current which is in a fixed ratio to the primary current. A transformer so used is sometimes called a "series transformer," or "current transformer." Further information about transformers and their connections is given in subsequent articles.

The crown of field poles of the exciter is arranged to be turned at will about the exciter armature as an axis. This adjustment, however, is usually made once for all at the factory.

Fig. 98 is a general view of a three-phase compensated field alternator of the General Electric Company.

In Fig. 99*a*, the revolving 8-pole field magnet of this alternator, together with the direct current armature and the commutator of the exciter, are shown mounted on the same shaft. Fig. 99*a* also shows the three collector rings which serve to carry the three-phase alternating currents from the stationary alternator armature into and through the armature of the exciter; and also the two collector rings for carrying the direct current from the exciter commutator to the revolving field coils of the alternator. Fig. 99*b* shows one bearing and all the brushes of the machine.

The stationary armature structure of this compensated alternator is shown in Fig. 99*c*, with the front shield and 8-pole stationary field of the exciter removed.

ELEMENTARY THEORY OF POLYPHASE ALTERNATORS AND SYSTEMS.—ARMATURE WINDINGS.

44. Limitations of the Single-Phase System. As long as alternating current was generated, transmitted, and used *for electric lighting* only, the single-phase system gave complete satisfaction. Simplicity in the generating, transmitting, and receiving apparatus was the most striking and valuable feature of this system.

In the earlier days of the electric lighting industry, there was very little, if any, demand for current to operate motors for power purposes. Since that time, however, there has developed an ever-increasing demand for current *for power purposes*, fully equaling if not exceeding that for lighting work. With the advent of this new condition, the great obstacle to the use of the single-phase alternating-current system became manifest. Single-phase motors are difficult to make self-starting* under load, especially in units of large size; and hence the use of the single-phase system for general power purposes, with the apparatus now available, is not practicable.

It was in 1888 that Ferarris, in Italy, discovered the important principle of the production of a rotating magnetic field by means of two or more alternating currents displaced in phase from one another, and he thus made possible, by means of the

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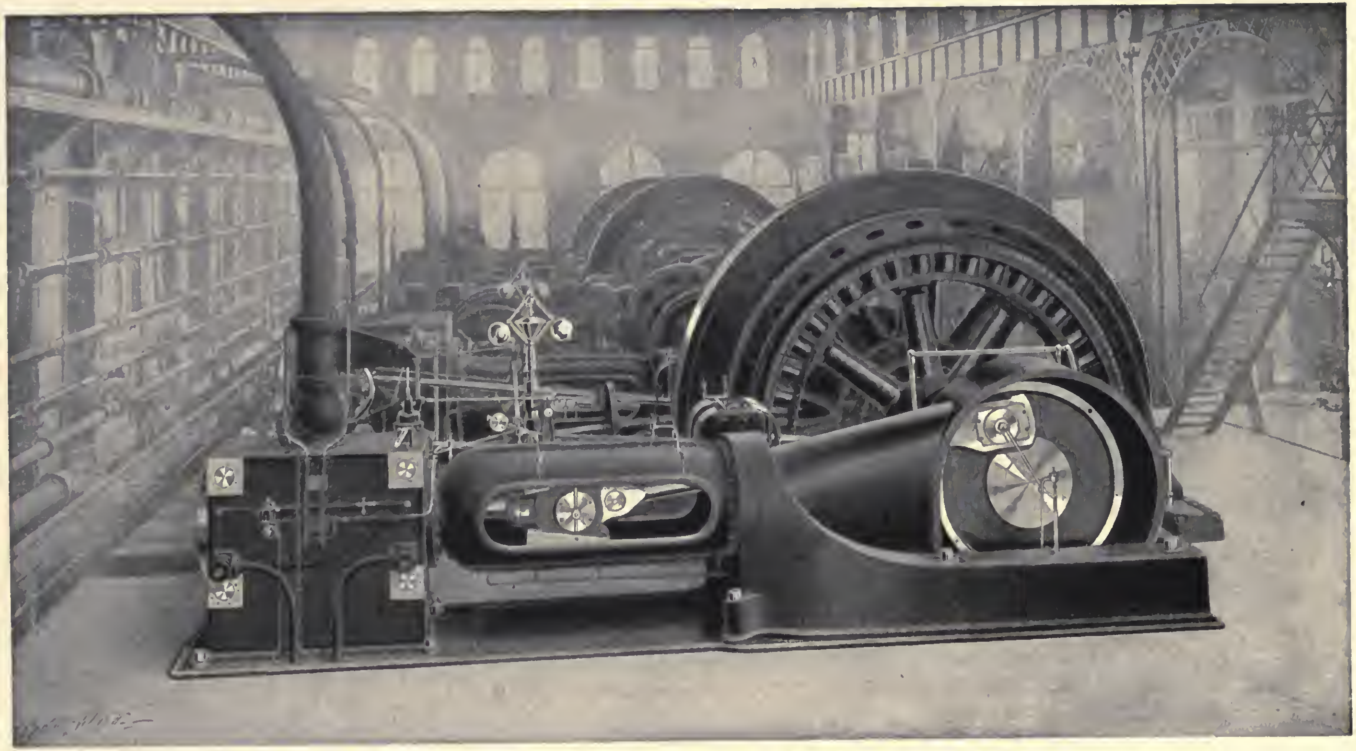
NOTE.—Except in special types.



THREE 2,500- H.P. CROSS-COMPOUND CONDENSING CORLISS ENGINES, OPERATING THREE-PHASE A.C. GENERATORS IN PARALLEL.
C. & G. Cooper Company.

induction motor, the use of polyphase currents for power purposes. *The most important advantage of polyphase alternating currents over the simple single-phase system is that alternating-current motors can be satisfactorily operated by them.* It was mainly the requirements of the induction motor that led to the development of the polyphase system.

45. The Two-Phase Alternator. The simplest form of polyphase generator consists of two similar and independent single-phase armatures mounted rigidly on one and the same shaft, one beside the other, in such a manner that the electromotive forces at the terminals of the respective armatures arrive at their maximum values 90°, or one-fourth of a period, apart. The currents from such a machine are said to have a **two-phase** relationship. The two separate armatures are supposed to revolve inside the same crown of field magnet poles.

Fig. 100 shows an end view of such an arrangement, but armature B is here shown inside of armature A for the sake of clearness. As will be seen in the figure, armatures A and B are so mounted on the shaft that the slots of A are midway *under* the poles NS when the slots of B are midway *between* the same poles. With this arrangement the electromotive force generated in the armature coils of A and B are so related in their variations that the electromotive force of A is at its maximum when the electromotive force of B is zero. Or in other words, the two electromotive forces are 90° apart in phase, or are in quadrature (at right-angles) to each other.

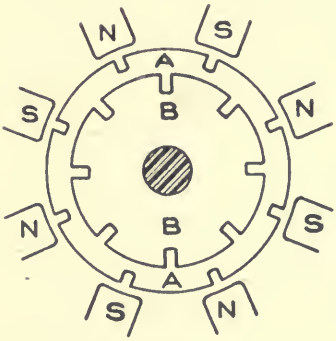


Fig. 100.

A careful study of Fig. 100 will show that the electromotive forces induced in armatures A and B are 90° apart in phase. Thus the figure shows the armature A in the position in which its windings (in the slots) are cutting lines of flux from the field poles at a maximum rate, while the armature B is shown in the position in which its windings are midway between the field poles where they do not cut any magnetic flux at all. Therefore the electromotive force in the windings of the armature A is at its maximum value, and the electromotive force in the windings of armature B is zero at the given instant.

The two equal, but distinct and independent electromotive forces generated by such a two-phase alternator are generally used to supply two distinct and separate currents to two distinct and independent circuits. When so used the system is called a **two-phase, four-wire system.** We shall see later that it is possible to interconnect the two circuits in such a manner that one of the four line wires may be omitted.

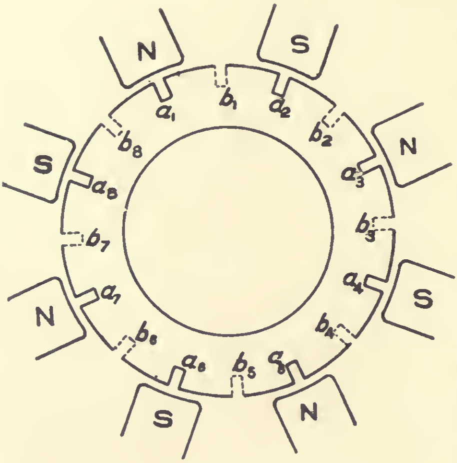


Fig. 101.

In practice the actual two-phase alternator is constructed by placing the armature windings of A and B upon one and the same armature core, instead of on separate cores. To accomplish this the armature body has twice as many slots as either A or B in Fig. 100. Fig. 101 shows such an armature. The slots marked a_1, a_2, a_3, etc., contain the conductors comprising phase A; whereas the slots marked b_1, b_2, b_3, etc., contain the conductors comprising phase B. The A winding passes in slot a_1 from front to back of the armature core; then towards the reader (that is, from back to front) in slot a_2; then from front to back in a_3, from back to front in a_4, and so on. The various conductors in slots a_1, a_2, a_3, etc., are joined in series by connectors (at front and back), and the two ends of the final series are connected to two collector rings.

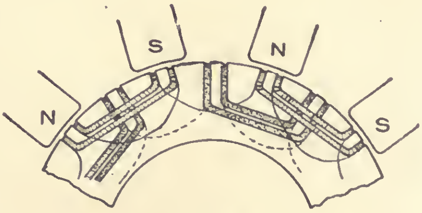


Fig. 102.

The B winding passes in slot b_1, from front to back of the armature core; then towards the reader (that is, from back to front) in slot b_2; then from front to back in b_3, from back to front in b_4, and so on. The various conductors in slots b_1, b_2, b_3, etc., are joined in series, and the two ends of the final series are connected to two collector rings, which rings are distinct from the pair of rings to which the A winding is connected.

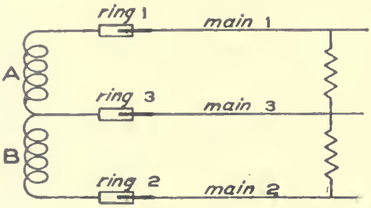


Fig. 103.

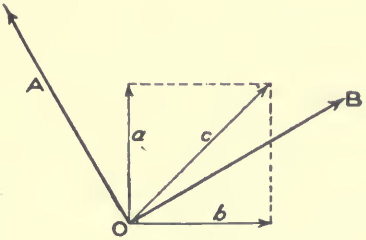


Fig. 104.

The armature windings A and B just described are of the **concentrated** or **uni-coil** type (see Art. 51), having only one slot per pole for each winding (*i.e.*, per phase). **Distributed (multi-coil)** windings also are frequently used for two-phase alternators. Thus, Fig. 102 shows an end view of a portion of a two-phase armature with its A and B windings each distributed in two slots per pole. The coils belonging to winding A are lightly shaded, and those belonging to winding B are darkly shaded in the figure. The connections between the coils of the A winding are shown in the figure by the full lines, while the connections of the B winding are shown by the dotted lines.

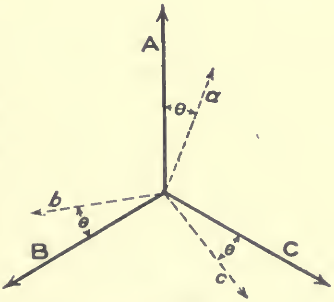


Fig. 105.

Two-phase alternators are usually provided with two sets of collector rings; one ring, however, may be made to serve as a common connection for the two armature windings, as shown in Fig. 103. The lines A and B in the clock diagram, Fig. 104, represent the generator electromotive forces, *a* represents the current in main 1, *b* represents the current in main 2, and *c* represents the current in the common main 3.

46. The Three-Phase Alternator. Consider three similar single-phase armatures A, B, and C, mounted side by side on the same shaft and revolved in the same field, each armature having as many slots as there are field poles. Fix the attention upon a certain armature slot of A, and let time be reckoned from the instant that this slot is squarely under an N-pole. Let *t* be the time which elapses as this armature slot passes from the center of one N-pole to the center of the next N-pole. The armature B is to be so fixed to the shaft that its slots are squarely under the poles at the instant $\frac{1}{3}t$; and the armature C is to be so fixed that its slots are squarely under the poles at the instant $\frac{2}{3}t$. While a slot passes from the center of one N-pole to the center of the next N-pole, the electromotive force passes through one complete cycle. Hence the electromotive forces given by three armatures arranged as above, will be 120° apart in phase, as shown in Fig. 105, in which the lines A, B, and C represent the respective electromotive forces. The currents given by the armatures to three similar receiving circuits lag equally behind the respective electromotive forces, and are represented by the dotted lines *a*, *b*, and *c*. This combination of three alternators is called a **three-phase alternator.** In practice the three distinct windings A, B, and C are placed upon one and the same armature body. For this purpose the armature body has three times as many slots as A, B or C.

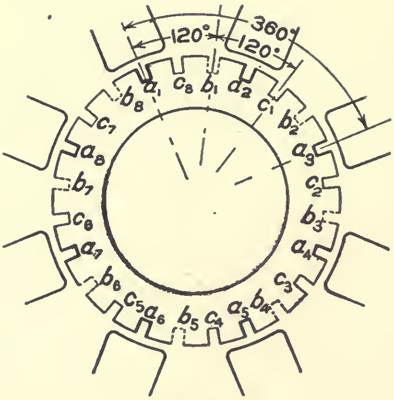


Fig. 106.

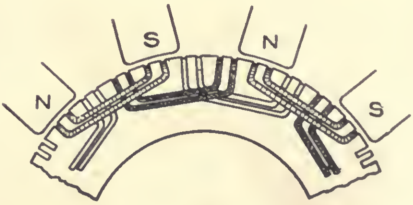


Fig. 107.

Fig. 106 shows the arrangement of the slots for such a winding. The slots belonging to phase A are drawn in heavy lines, and are marked a_1, a_2, etc. Those belonging to phase B are shown dotted, and those belonging to phase C are shown in light lines. The A winding would pass up slot a_1, down a_2, up a_3, etc., the B winding, up b_1, down b_2, up b_3, etc.; and similarly for winding C.

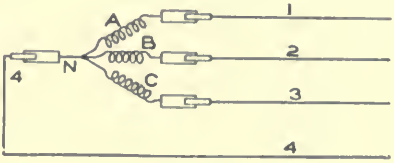


Fig. 108.

The windings A, B, and C here described are of the concentrated type, having only one slot per pole for each winding. Distributed windings also are frequently used for three-phase alternators. Thus Fig. 107 shows a portion of a three-phase armature with its A, B, and C windings each distributed in two slots per pole. The coils belonging to windings A, B, and C respectively are differently shaded to distinguish them. The manner of connecting the coils of each winding is described in Art. 51.

If the three circuits of a three-phase alternator are to be entirely independent, six collector rings must be used, two for each winding; however, the circuits may be kept practically independent by using four collector rings and four mains, as shown in Fig. 108. The main 4 serves as a common return wire for the independent currents, in mains 1, 2, and 3. When the three receiving circuits are equal in resistance and reactance (that is, when the system is balanced), the three currents are equal, and are 120° apart in phase (each current lagging behind its electromo-

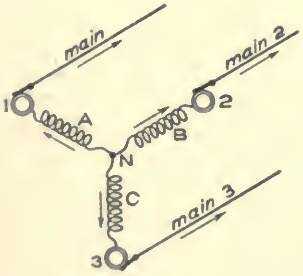


Fig. 109.

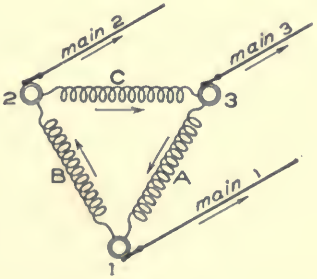


Fig. 110.

tive force by the same amount as the others); and their sum is at each instant equal to zero. In this case, main 4, Fig. 108, carries no current; and this main and the corresponding collector ring may be dispensed with, the three windings being connected together at the point N, called the **common junction** or **neutral point.** This arrangement, shown in the symmetrical diagram, Fig. 109, is called the "Y" or "star" scheme of connecting the three windings A, B, and C.

Another scheme for connecting the three windings A, B, and C (also for balanced loads), called the "Δ" (delta) or "mesh" scheme, is illustrated in Fig. 110. Winding (or phase) A is connected between rings 3 and 1; winding (or phase) B between rings 1 and 2; and winding (or phase) C between rings 2 and 3.

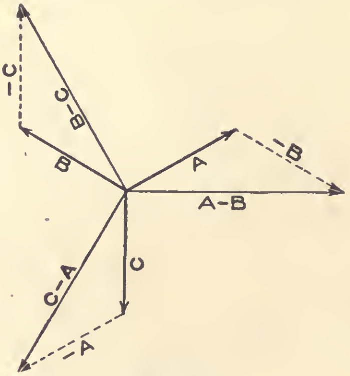


Fig. 111.

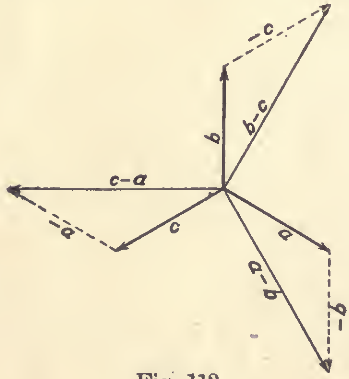


Fig. 112.

The direction in a circuit in which the electromotive force or current is considered as a positive electromotive force or current, is called the **positive direction** through the circuit. This direction is chosen arbitrarily. The arrows in Figs. 109 and 110 indicate the positive directions in the mains and through the windings. It must be remembered that these arrows represent not the actual directions of the electromotive forces or currents at any given instant, but merely the directions of *positive* electromotive forces or currents. Thus, in Fig. 109, the currents are considered positive when flowing from the common junction towards the collecting rings, and the currents are never all of the same sign.

47. Electromotive Force and Current Relations in Y-Connected Armatures. *Electromotive Force Relations.* We shall consider the electromotive force between mains 1 and 2, Fig. 109, to be positive, where it tends to push current through a receiving circuit from main 1 to main 2. Similarly, the electromotive force between mains 2 and 3 is considered positive, from main 2 to main 3; and the electromotive force between mains 1 and 3 is considered positive, from main 3 to main 1. Passing through the windings A and B from ring 2 to ring 1, Fig. 109 (which is the direction in which an electromotive force must be generated to give an electromotive force acting upon a receiving circuit from main 1 to main 2), the winding A is passed through in the positive direction, and the winding B in the negative direction. Therefore the electromotive force from main 1 to main 2 is A – B. Similarly the electromotive force from main 2 to main 3 is is B – C, and the electromotive force from main 3 to main 1 is C – A. These differences are shown in the clock diagram, Fig. 111. The electromotive force between mains 1 and 2 (namely, A – B) is 30° behind A in phase, and its effective value is $2E \cos 30^\circ = \sqrt{3}\,E$, where E is the common value of each of the electromotive forces A, B, and C. Similar statements hold concerning the electromotive forces between mains 2 and 3, and those between mains 3 and 1. Hence the electromotive force between any pair of mains leading from a three-phase alternator with a Y-connected armature is equal to the electromotive force generated per phase multiplied by $\sqrt{3}$.

Current Relations. In the Y connection the currents in the mains are equal to the currents in the respective windings, as is evident from Fig. 109.

48. Electromotive Force and Current Relations in Δ-Connected Armatures. *Electromotive Force Relations.* In Δ-connected armatures the electromotive forces between the mains or collector rings are equal to the electromotive forces of the respective windings, as is evident from Fig. 110.

Current Relations. Referring to Fig. 110 we see that a positive current in winding A produces a positive current in main 1, and that a negative current in winding B produces a positive current in main 1; therefore the current in main 1 is $a - b$, where a is the current in winding A, and b is the current in winding B. Similarly, the current in main 2 is $b - c$, and the current in main 3 is $c - a$. These differences are shown in Fig. 112. The current in main 1 (namely $a - b$) is 30° behind a in phase; and its effective value is $\sqrt{3}\,\mathrm{I}$, where I is the common effective value of the currents, a, b, c in the different phases. Similar statements hold for the currents in mains 2 and 3; so that the current in each main from a Δ-connected armature is $\sqrt{3}$ times the current in each winding.

49. Connection of Receiving Circuits to Three-Phase Mains. *Dissimilar Circuits* (*Unbalanced System*). When the receiving circuits which take current from three-phase mains are dissimilar, four mains should be employed, as indicated in Fig. 108; each receiving circuit being connected from main 4 to one of the other mains. It is, however, desirable to keep the three windings A, B, and C of the alternator nearly equally loaded; and in practice the receiving circuits are so disposed as to satisfy this condition as nearly as possible.

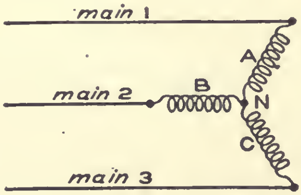


Fig. 113.

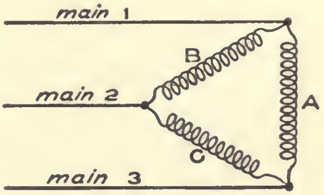


Fig. 114.

Similar Circuits (*Balanced System*). When three-phase currents are used to drive induction motors, synchronous motors, or rotary converters, each one of these machines takes current equally from the three mains; and since three-phase currents are utilized chiefly in the operation of the machines mentioned, the system is usually balanced. In this case three mains only are employed, and each receiving unit has three similar receiving circuits connected to the mains according to either Y or Δ method. The Y method of connecting receiving circuits is shown in Fig. 113. One terminal of each receiving circuit is connected to a main, and the other terminals are connected together at the neutral point N. In this case the current in each receiving circuit is equal to the current in the main to which it is connected. The electromotive force between the terminals of each receiving circuit is equal to $\frac{E}{\sqrt{3}}$, where E is the electromotive force between any pair of mains.

The Δ method of connecting receiving circuits is shown in Fig. 114. Here the three receiving circuits are connected between the respective pairs of mains; the electromotive force acting on each receiving circuit is the electromotive force between the mains; and the current in each receiving circuit is $\frac{I}{\sqrt{3}}$, where I is the current in each main.

Examples. 1. The three windings or phases of a three-phase induction motor are Y-connected to three-phase mains. The voltage between mains is 500, and each main delivers 25 amperes to the motor. It is required to find the current in each phase of the motor, and the electromotive force acting on each phase of the motor.

Since the windings are Y-connected, the current in each is the same as the current in each main—namely, 25 amperes; and the electromotive force acting on each phase of the motor winding is $\frac{500}{\sqrt{3}}$, or 288.7 volts.

2. The three phases of the above three-phase induction motor are Δ-connected to three-phase mains. The voltage between mains in 288.7, and the current in each main is 43.3 amperes. It is required to find the current in each phase of the motor, and the electromotive force acting on each phase of the motor.

Since the windings are Δ-connected, the electromotive force acting on each phase is the same as the voltage between the mains —namely, 288.7 volts; and current in each phase of the motor is $\frac{43.3}{\sqrt{3}}$ or 25 amperes.

Summary of Electromotive Force and Current Relations for Δ and Y Connections in Three-Phase Systems. Let E_w be the rated electromotive force of each winding, and I_w the rated full-load current output of each phase of the winding of a three-phase alternator. Then, for a generator with non-inductive load, we have:

	E.M.F. Between Mains.	Current in Each Main.	Power Rating.
Δ connection.......	E_w	$\sqrt{3}\, I_w$	$\sqrt{3}\, E_w I_w$
Y connection	$\sqrt{3}\, E_w$	I_w	$\sqrt{3}\, E_w I_w$

Let E be the electromotive force between mains of a three-phase system, and let I be the current in each main. Then, for three receiving circuits, we have:

	E.M.F. Between Terminals of Each Receiving Circuit.	Current in Each Receiving Circuit.
Δ connection.............	E	$\frac{I}{\sqrt{3}}$
Y connection.............	$\frac{E}{\sqrt{3}}$	I

The permissible power output or rating of a three-phase alternator is the same whether its armature windings are Y-connected or Δ-connected.

The power output of a three-phase generator is $\sqrt{3}$ × *electromotive force between mains* × *current in one main* × *power factor of the receiving circuits.*

50. Measurement of Power in Polyphase Systems. In alternating current circuits, power cannot in general be measured by means of an ammeter and a voltmeter, as in the case of direct current, because the power expended is generally less than the product of effective electromotive force and effective current on account of the difference in phase between the electromotive force and the current.

A well-designed wattmeter is the standard instrument for measuring power in alternating-current circuits, and the methods involving its use are the most generally satisfactory.

The discussion of the wattmeter given in Arts. 36 and 37 applies primarily to the use of the wattmeter for the measurement of power delivered in single-phase systems.

The several circuits of a polyphase system are often entirely separate and independent; and in such cases the total power delivered to a receiving apparatus is found by measuring the power delivered to each separate receiving circuit. The total power delivered is the sum of the amounts delivered to the different receiving circuits.

In order to measure the power delivered to one of the receiving circuits of a polyphase system, the current coil of the wattmeter is to be connected *in series* with this receiving circuit, and the pressure (or voltage) coil of the wattmeter is to be connected *between the terminals* of this receiving circuit. In some cases this connection of the voltage coil cannot be made, because one terminal of the receiving circuit may be out of reach in the interior of the apparatus.

Balanced Systems. In general, the several circuits which receive current and power from polyphase mains are more or less unlike in both resistance and reactance, and take different amounts of current and power from the mains. It is, however, desirable that the several receiving circuits be alike, so that they may take equal currents and equal amounts of power from the mains. When this condition is realized, the system is said to be **balanced.**

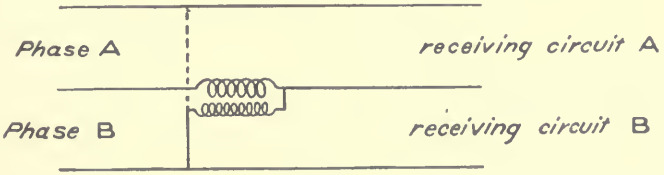


Fig. 115.

Examples. When independent groups of lamps are supplied from polyphase mains, each group taking current directly or through a transformer from one phase of the polyphase system, the system is said to be **unbalanced** when the number of lamps is not the same in the several groups. In general, the supply of power to several separate, independent, and unrelated receiving circuits, such as independent groups of lamps and single-phase motors, leads to the unbalancing of a polyphase system. Apparatus such as polyphase induction motors, synchronous motors, and rotary converters, which is especially designed to take power from polyphase mains, is always provided with two or three similar receiving circuits so as to take equal amounts of current and power from each phase of the system. When such polyphase apparatus, only, takes power from polyphase mains, the system is always very nearly balanced.

If a polyphase system were exactly balanced it would be sufficient to measure the power delivered by one phase only; but since a balanced condition of system is seldom exactly realized in practice, there may be considerable error introduced by assuming that a system is balanced, and by calculating the total power from the wattmeter reading of power delivered by one phase only.

In balanced or approximately balanced polyphase systems, the measurement of power by use of a single wattmeter is best accomplished by special arrangement of connections as follows:

Balanced Three-Wire Two-Phase Systems. The current coil of the wattmeter should be connected in the middle main as shown in Fig. 115. After a reading is taken with the pressure coil connected between middle and lower mains, this connection is quickly changed to the upper main, as indicated by the dotted line, and the wattmeter again read. The sum of the two successive readings gives the total power. If this method is used, the system should not only be balanced, but no change in the load should occur between readings.

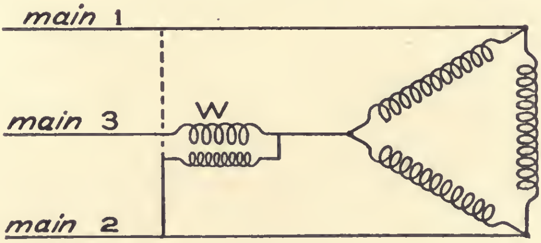


Fig. 116.

Example. The power taken by a two-phase induction motor is measured by a wattmeter connected as shown in Fig. 115 When the wattmeter is connected as shown by the full line in the figure, it reads 9,900 watts. When the wattmeter is connected as shown by the dotted line, it reads 1,415 watts. The total of watts delivered is therefore 11,315 watts, the two phases of the motor being assumed to be balanced. Each phase of the motor receives therefore $\frac{11,315}{2} = 5,657$ watts. The current delivered to each phase, as measured by an alternating current ammeter is 32.14 amperes; and the electromotive force acting on each phase of the motor, that is, between the terminals of each receiving circuit, is 220 volts. The apparent power (volt-amperes) delivered to each phase, is 220 volts × 32.14 amperes = 7,071 apparent watts; and the power factor of each receiving circuit is

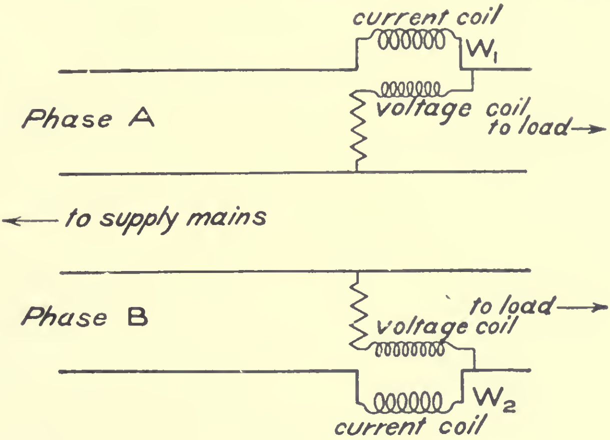


Fig. 117.

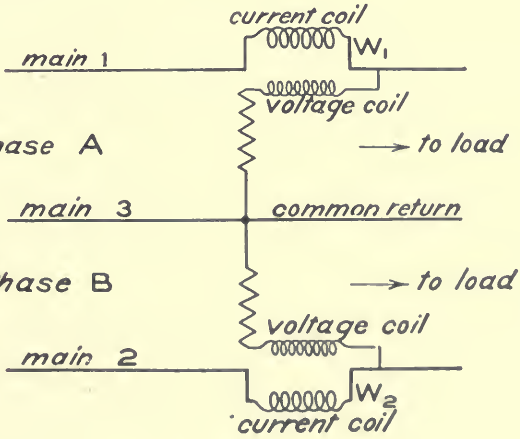


Fig. 118.

$$\frac{5,657 \text{ watts}}{7,071 \text{ apparent watts}}, \text{ or } 0.80.$$

The two readings of a wattmeter connected, as shown in Fig. 115, are unequal, even though the receiving circuits are balanced, because of the effect of lagging currents; or, in other words, because the two receiving circuits are inductive.

It is to be carefully noted that, in general, neither reading of the wattmeter measures the power delivered to either one of the receiving circuits.

Balanced Three-Wire Three-Phase Systems. The current coil of the wattmeter should be connected in series with one (any one) of the three mains, as shown in Fig. 116. After one reading of the wattmeter is taken with the voltage coil connected to main 2, as indicated by the full line, the connection is quickly changed to main 1, as indicated by the dotted line. and a second reading of the wattmeter taken. The total power delivered to the three similar (that is, balanced) phases, is equal to the sum of the two readings.

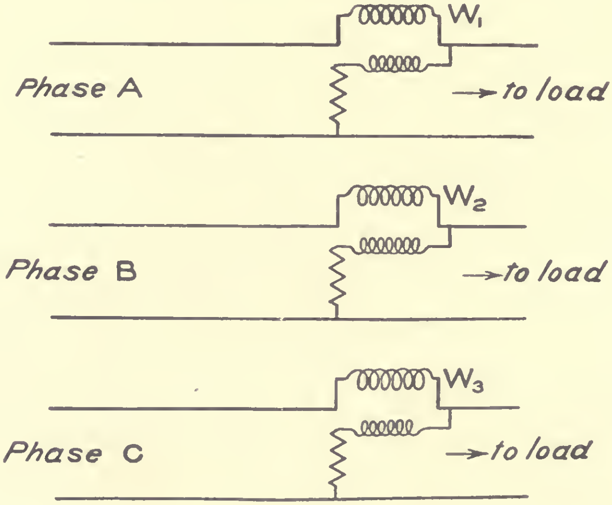


Fig. 119.

Unbalanced Two-Phase Systems. In general, any receiving apparatus is sufficiently unbalanced to require the measurement of power to be made on the assumption that the receiving circuits are unbalanced.

Four-Wire Two-Phase. When four mains are used, two for each separate phase, then two wattmeters are required, one for measuring the power delivered by each phase. Each of these wattmeters is connected exactly as in the case of single-phase delivery of power, as shown in Fig. 117. The sum of the readings $W_1 + W_2$ of the two wattmeters gives the total power delivered. Two readings should, of course, be taken as nearly simultaneously as possible.

Three-Wire Two-Phase. When a two-phase system is balanced or unbalanced and has three supply mains, one main acting as the common return for the other two, then the arrangement shown in Fig. 118 gives the best results. The total power delivered to the receiving circuit is the sum $W_1 + W_2$ of the readings of the two wattmeters. The readings should be taken as nearly simultaneously as possible.

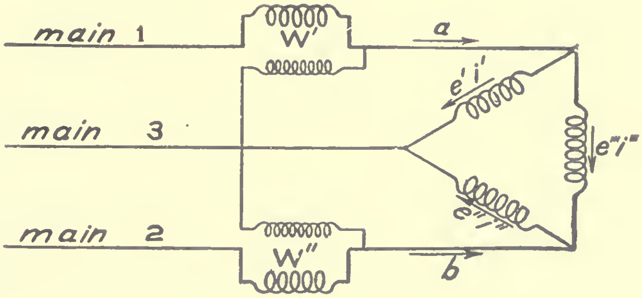


Fig. 120.

Unbalanced Three-Phase Systems. *Six-Wire Three-Phase.* When six mains are used, two for each separate phase, then three wattmeters are required, one for measuring the power delivered by each phase. Each of these wattmeters is connected exactly as in the case of single-phase delivery of power, as shown in Fig. 119.

In practice, six wires are never used for three-phase systems on account of complications and the excessive amount of copper required.

Three-Wire Three-Phase. When three mains are used in a three-phase system, two wattmeters are sufficient for the complete measurement of the power delivered to any three-phase receiving unit, whether the receiving circuit is balanced or unbalanced, or whether it is connected Y or Δ.

Fig. 120 shows two wattmeters connected for measuring the power delivered to a Δ-connected three-phase receiving system.

The algebraic sum of the readings of the two wattmeters gives the total power delivered independent of balance or lag. When the current lag in the circuit is less than 60° (*i.e.*, when the power factor is greater than 0.5), then the arithmetical *sum* of the readings of the two wattmeters gives the total power. But if the lag is greater than 60° (the power factor less than 0.5), the relation of the currents in the current and pressure coils of one of the wattmeters causes it to give a negative reading; hence the arithmetical *difference* of the readings of the two instruments gives the power.

There may be a difficulty in determining which condition exists in some cases, especially when the power delivered to partially loaded induction motors whose power factor is low, is to be measured. In such cases one may determine whether the sum or difference of readings is to be taken, by interchanging the position of the instruments without changing the relative connections of their current and pressure coils. If the deflections of both pointers are now reversed, the difference of the original readings gives the true power. But if the deflections are in the same direction as before, the sum of the original deflections is the correct power.

Proof of Method. Let the positive direction in the mains 1 and 2 and in the three receiving circuits be chosen as indicated by the arrows in Fig. 120. These directions are chosen symmetrically with respect to the two wattmeters. Let the instantaneous currents in the receiving circuits be i', i'', and i''', as shown in the figure. Let a be the instantaneous current in main 1, and let b be the instantaneous current in main 2. Then, from the arbitrary choice of signs,

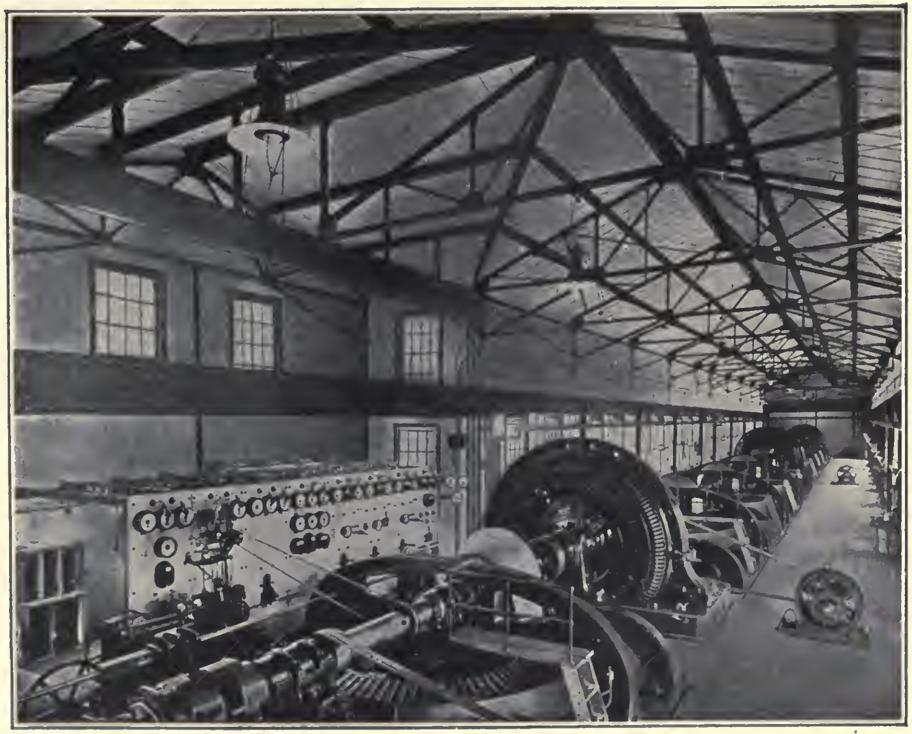
$$a = i' + i''';$$
$$b = i'' - i'''.$$

The reading W′ of the upper wattmeter is equal to the average value of the product of the current a, which flows through the current coil of the instrument, and the electromotive force e', which is acting upon the pressure coil of the wattmeter. That is,

$$W' = \text{average } (ae').$$

Similarly, the reading W″ of the lower wattmeter gives:

$$W'' = \text{average } (be'').$$



THREE 500 K. W. COUPLED TYPE A. C. GENERATORS, 6,600 VOLTS, 25 CYCLES
Westinghouse Electric & Manufacturing Co.

Substituting the above values of a and b in the expressions for W' and W', and adding results, we have:

$$W' + W'' = \text{average } (e'\ i') + \text{average } (e''\ i'') + \text{average } (e' - e'')\ i'''.$$

But, from the figure, $e' - e'' = e'''$; hence

$$W' + W'' = \text{average } (e'\ i') + \text{average } (e''\ i'') + \text{average } (e'''\ i''').$$

Although a formal proof of the principle of the two-wattmeter method has not been given for a Y-connected circuit, it is not necessary to show independently that it holds for both cases. A little consideration will show that if the electromotive forces acting between the three wires, the currents flowing in them, and their phase relations are given, there is then a perfectly definite amount of power transmitted along the three lines, and it is quite immaterial whether this power is being delivered to circuits connected Δ or Y.

ARMATURE WINDINGS.

51. In general, any direct-current armature winding may be used for the armature of an alternator; but the desirability of generating comparatively high voltages in the armature so as to avoid the use of step-up transformers, makes it necessary to abandon the styles of winding best suited to direct-current machines, and to use windings specially adapted to the conditions of alternating-current practice.

Comparing the armature windings used for direct-current machines with those for alternators, we find, first, that all the re-entrant (or closed-coil) direct-current windings must necessarily be two-circuit or multiple-circuit windings. That is, they must have at least two paths in parallel through the armature between brushes. On the other hand, the armatures of alternators (and synchronous motors) may, and generally do, from practical considerations, have one-circuit windings, *i.e.*, windings having one circuit per phase. It follows therefore that any direct-current winding may be used for alternating-current machines; but the converse statement, that any alternating-current winding may be used for direct-current machines, is not true in general. In other words, the windings of alternating-current armatures are essentially non-reëntrant (or open-circuit) windings. The only exceptions are the Δ-connected (or mesh-connected) polyphase windings, and the short-circuited windings of "squirrel-cage" induction motors, both of which are reëntrant (or closed-circuit) windings. The Δ-connected polyphase windings are, therefore, the only windings that can be used for the armatures of rotary converters (machines for converting alternating to direct current or *vice versa*; described later).

In the type of winding generally employed for alternators, a number of distinct coils are arranged on the armature, in these coils, alternating electromotive forces are induced as they pass the field magnet poles, and the several coils are connected in series between the collecting rings.

Armatures for alternators, just as in the case of direct-current machines, may be divided into:

1. Drum Armatures.
2. Ring Armatures.
3. Disc Armatures.

Of these the RING and the DISC ARMATURES are seldom used in America although they are to some extent adopted in European practice.

The ring and the disc types of armature are mechanically less stable than the drum type; and the ring armature, moreover, other things being equal, requires more wire to be wound upon it for a given output than in the case of the **drum armature,** and possesses, therefore, a greater inductance than the latter type. Drum armatures, whether the alternators are of the revolving or stationary armature type, have laminated iron cores similar in construction to the armature cores for direct-current machines. Disc armatures, on the other hand, are usually made up without iron, thus introducing constructional difficulties.

With reference to the construction of their cores, the armatures of alternators may be classified, as in the case of direct-current machines, into:

1. Smooth-core Armatures.
2. Toothed-core Armatures.

1. In the **smooth-core armature** the conductors, arranged in flat coils, lie on the surface of the armature core, and the coils in some cases are bent down over the ends of the core, where they are fastened by end plates or by blocks of wood or fiber. The spaces

in the centers of the coils are filled with wooden blocks either screwed to the cores or held in place by the binding wires. In other cases the coils are flat or "pan-cake" shaped, and of the same length as the armature core. In the latter case they are laid upon the cylindrical surface of the armature core, and are securely bound with wire bands.

The form of the wave of electromotive force produced by smooth-core armatures is very nearly harmonic (sinusoidal) or slightly flat-topped. The inductance of a smooth-core (or surface-wound) armature is considerably less than that of a toothed-core armature. Although much used in earlier designs, the smooth-core armatures have, owing largely to their comparatively weak mechanical structure, been superseded in modern practice by the toothed-core constructions.

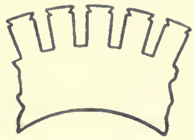


Fig. 121.

2. One or another of the forms of **toothed-core armature** is now almost universally used in practice. The conductors are laid in slots (or grooves) the sides and bottom of which are first carefully insulated by troughs of mica-canvas, micanite, or other suitable insulating material. The insulated conductors (cotton covered) are generally wound into coils on "formers," each coil being carefully taped, and are then impregnated with insulating compound (or varnish). The coils are then thoroughly dried by baking in ovens.

The conductors being enclosed in slots between teeth which project more or less over the conductors, the tooth-core type is often called **iron-clad.** This construction has three great advantages over the smooth-core type:

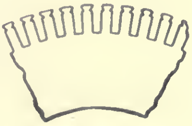


Fig. 122.

(*a*) It allows the length of air-gap from iron of pole-face to iron of armature core to be reduced to a minimum; just enough for mechanical clearance. Other things being equal, this means a saving in the copper required to magnetize the field.

(*b*) It protects the embedded conductors from injury.

(*c*) It affords an admirable way of supporting and securing the conductors firmly in place against the action of centrifugal force; and, further, it shields the conductors almost completely from the racking action of the magnetic drag due to the magnetic field.

The shape and number of the slots in a toothed armature core have a marked effect on the shape of the electromotive force wave, and upon the regulation of the alternator.

Fig. 121 shows a portion of an armature-core disc or stamping for a 12-pole, uni-tooth (one slot per pole per phase), three-phase alternator. The armature winding adapted to this uni-tooth core is, of course, the uni-coil or concentrated winding. The armature coils are held in place in the slots by wedges of wood or fiber driven in from the end of the core and fitting into notches near the tops of the teeth, as shown in the figure. This construction, now almost universally adopted by manufacturers, avoids the necessity for any binding wire on the armature core.

Alternators with uni-tooth armature cores are characterized by large armature inductance and by peaked-wave shapes of the induced electromotive forces; also by marked variations in the shape of the wave of induced electromotive force, according to the magnitude and power factor of the load.

On account of their comparatively large inductance, uni-tooth armature constructions require relatively large increase in the field-exciting current in passing from no load to full load. In other words, regulation is poorer than for multi-tooth armature cores.

According to present practice in design, the great majority of alternators are constructed with armature-core stampings having two or three slots per pole per phase. Fig. 122 shows a portion of an armature-core stamping for a 12-pole, three-phase alternator. It has three slots per pole per phase. The slots are open, which, together with the distributed (multi-coil) type of winding, results in a low armature inductance. This means that a relatively small increase in the field-exciting current is required in passing from no load to full load output.

Alternators with multi-tooth armature cores are especially adapted for long-distance transmission where step-up transformers are used. The regulation is better than with the uni-tooth core construction; and the wave shape of the electromotive force generated by the distributed winding approaches a sine wave, which is the best wave shape for the long-distance transmission of power. This is because of the fact that the nearer a given curve of electromotive force approaches a sine curve, the less the likelihood of a dangerous rise of voltage (resonance) occurring at the distant end of a long transmission line because of the capacity (condenser) effect.

With reference to the progress of the winding from slot to slot, armature windings may be divided into:

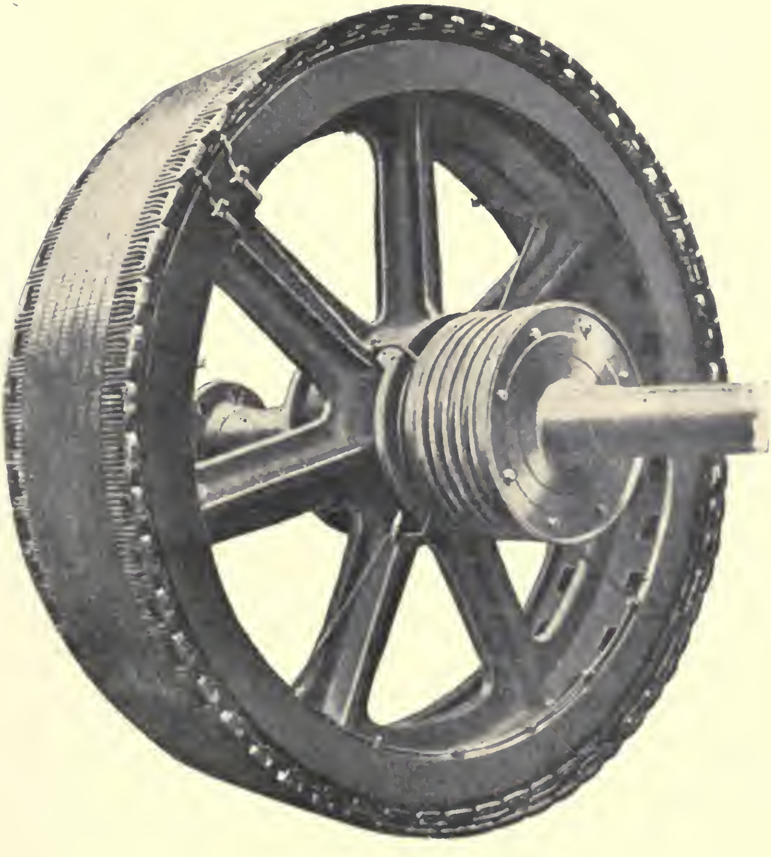


Fig. 123.

1. Spiral or Ring Windings.
2. Lap Windings.
3. Wave Windings.

These terms have the same meaning when applied to alternator windings as they do when applied to the windings of direct-current machines.

With reference to the disposition of the coils around the periphery of the core, we have to distinguish between two general classes:

1. Concentrated or Uni-coil Windings.
2. Distributed or Multi-coil Windings.

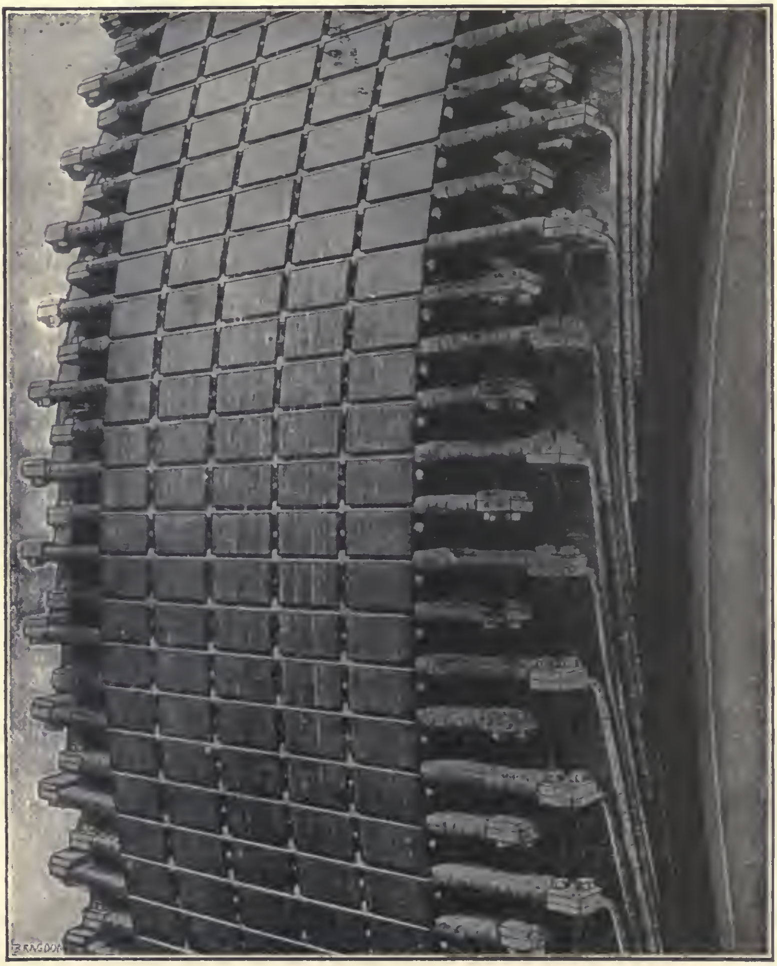


Fig. 124.

1. **Concentrated** or **uni-coil windings,** as the name implies, consist of one coil per pole per phase. The armature conductors are thus grouped in bundles, and usually placed in slots, there being one slot per pole for each phase.

2. **Distributed** or **multi-coil windings** consist of several coils per pole per phase. The armature conductors are distributed in two or more slots per pole per phase.

Examples of concentrated windings are shown in Figs. 1 (Part I.) and 85, in which the armature conductors are shown as lying in one slot per pole Fig. 1 shows adjacent sides of two different armature coils lying in one slot. In some cases, each slot is filled by one side of a single armature coil.

Examples of distributed windings are shown in Figs. 102 and 107. Fig. 102 shows an end view of a two-phase winding distributed in two slots per pole per phase. Fig. 107 shows an end view of a three-phase winding distributed in two slots per pole per phase.

Concentrated windings are less expensive to make ; and they give a greater effective electromotive force (at zero load) for a given number of conductors, other things being equal, than distributed windings. This is on account of the fact that all the conductors of a concentrated winding cut the field flux simultaneously, while the various conductors of a distributed winding do not cut the field flux simultaneously.

Concentrated windings have greater inductance than distributed windings for the same total number of conductors, and also give a greater armature reaction for a given current than distributed windings. Consequently the terminal electromotive force of an alternator falls off more with concentrated windings than with distributed windings, when the current output is increased. Therefore an alternator with a concentrated winding has poorer regulation than an alternator with a distributed winding ; and although a concentrated winding may give a higher electromotive force at zero load, it may actually give a lower electromotive force at full load.

According to the form of the conductors used, armature windings may be divided into three classes, as follows :

1. Wire Winding.
2. Strap Winding.
3. Bar Winding.

1. **Wire Winding,** which is usually employed in high-voltage machines of low-current output, consists of machine-wound coils, which are entirely formed and insulated before being placed in the armature slots.

2. **Strap Winding** is used for machines of lower voltage and of greater current output, and it consists of copper strap forged into the required shape and carefully insulated.

Both the wire and strap windings are placed in the slots without any mechanical bending, thus preventing damage to the insulation. In armature cores having the slots partially closed, the winding is slipped in from the end; but in cores having open slots, wedges of hard fibre secure the coils in place.

Fig. 123 is an illustration of strap winding distributed in four slots per pole per phase. The completed armature, ready for direct connection to a steam engine, is shown in the figure, and is intended to revolve inside of a stationary field magnet. The four collector rings indicate that the armature is wound for two phases. It is manufactured by the Westinghouse Company.

3. **Bar Windings** are held in place by the overhanging tips of the teeth. The bars, after being carefully insulated, are slipped into the slots from one end of the armature. The end connections of the bar winding are bolted and soldered to the bars after the conductors are in place.

Bar windings are usually executed with either one or two bars per slot. There are no band wires on the armature core.

Fig. 124 shows a portion of a bar-wound revolving armature having one bar per slot.

Single-Phase Windings. Fig. 1 shows a common type of single-phase winding having one coil per pole. Fig. 125 shows another type of concentrated single-phase winding, having one coil to each pair of poles or one slot per pole. The sketch *b*, Fig. 125, is a sectional view of a portion of the armature core, showing one of the slots containing the conductors forming one side of a single armature coil and standing opposite to a field pole. In the diagram, Fig. 125, the heavy sector-shaped figures represent the coils, and the light lines represent the connections between the terminals of the coils. The radial parts of the sector-shaped figures represent the portions of the coils that lie in the slots, and the curved parts represent the ends of the coils. The circles at the center of the figure represent the collecting rings, one being

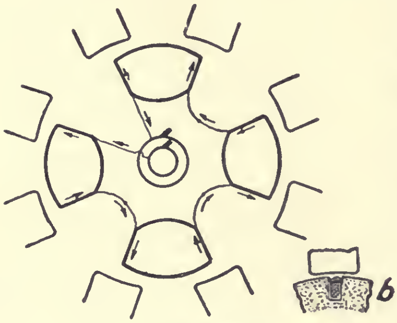


Fig. 125.

shown inside the other for clearness. The arrows represent the direction of the current at a given instant. All electromotive forces under N poles are in one direction, and all electromotive forces induced under S poles are in the opposite direction. These remarks apply to Figs. 125 to 132 inclusive.

Fig. 126 represents a single-phase winding distributed in two slots per pole, all the coils being connected in series. The sketch *b*, Fig. 126, is a sectional view of a portion of the armature core, showing two slots.

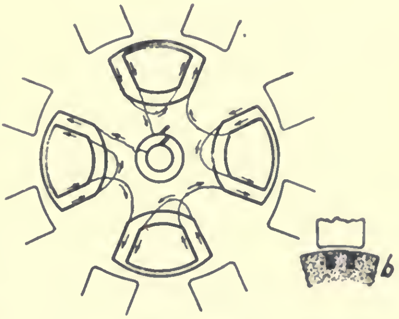


Fig. 126.

Two-Phase Windings. The two-phase winding consists of two independent single-phase windings on the same armature, each being connected to a separate pair of collecting rings, as shown in Figs. 127 and 128 Fig. 127 shows a two-phase concentrated winding, one slot per pole for each phase. Fig. 128 shows a two-phase winding distributed in two slots per pole for each phase. In each of the figures (127 and 128), the winding of one of the phases is shown by dotted lines, to distinguish it from that of the other.

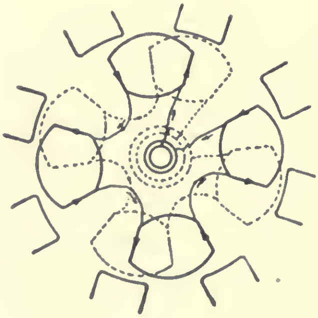


Fig. 127.

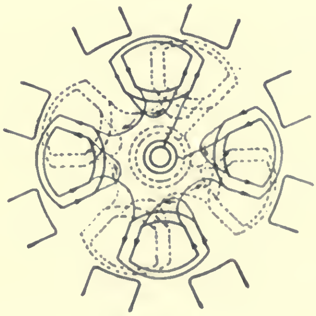


Fig. 128.

Three-Phase Windings. The three-phase winding consists of three independent single-phase windings on the same armature. the terminals of the individual windings being connected according to the Y scheme or Δ scheme, as explained in article 46. Fig. 129 shows a three-phase concentrated winding (one slot per pole for each phase), Y-connected. Fig. 130 shows the same winding Δ-connected. In Figs. 129 and 130 the winding of phase A is shown by heavy full lines; the winding for phase B is shown by light full lines; and the winding for phase C is shown by dotted lines.

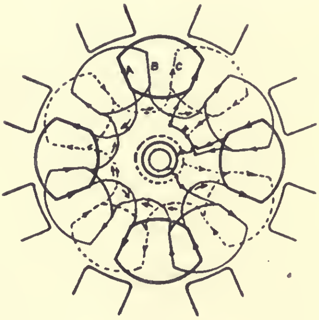


Fig. 129.

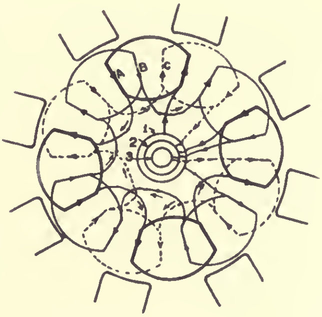


Fig. 130.

The Y connection gives $\sqrt{3}$ times as much electromotive force between collecting rings as the Δ connection for the same total number of conductors per phase, and is the more suitable for high electromotive force machines. The Δ connection, on the other hand, is especially adapted for machines for large current output. The line current is $\sqrt{3}$ times as great as the current in each winding in a Δ-connected armature.

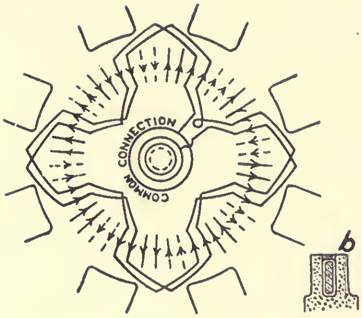


Fig. 131.

Fig. 131 shows a three-phase bar winding distributed in two slots per pole for each phase. The sketch *b*, Fig. 131, is a sectional view of one slot containing a single conductor in the form of a rectangular bar.

Fig. 132 shows a three-phase coil winding distributed in two slots per pole for each phase and arranged in two layers, there being as many coils on the armature as there are slots, so that portions of two coils lie in each slot, one above the other. The portions of the coils represented by full lines lie in the upper parts of the slots, and the adjacent dotted portions lie in the bottoms of the same slots. The sketch *b*, Fig. 132, is a sectional view of one slot showing two half-coils one above the other, thus constituting a two-layer winding.

The method of connecting up the separate windings of a three-phase alternator is as follows:

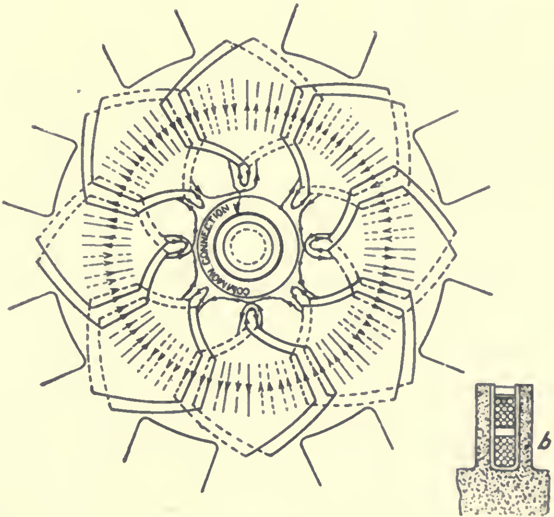


Fig. 132.

The Y Connection. The terminals of the individual windings which are to be connected to the common junction and to the collecting rings, may be determined as follows: Consider the instant when winding A is squarely under the poles, as shown in Fig. 129. The electromotive force in this winding (and the current also, if the circuit is non-inductive) is a maximum, and the currents in the other two phases B and C are each half as great. If winding A is connected so that its current is flowing away from *k*, windings B and C must be connected so that their currents flow towards *k*.

The Δ Connection. The three windings form a closed circuit when Δ-connected. The total electromotive force around this circuit at any instant must be zero. Consider the instant when winding A is squarely under the poles, as shown in Fig. 130. The electromotive force in this winding is a maximum, and the electromotive forces in the other two windings are each half as great. Then winding A is connected to any pair of rings, say 1 and 2; winding B is connected to ring 3 and ring 1 (or 2); and winding C is connected to ring 3 and ring 2 (or 1); these connections are made so that the electromotive forces at the given instant are in the directions indicated by the arrows in Fig. 130.

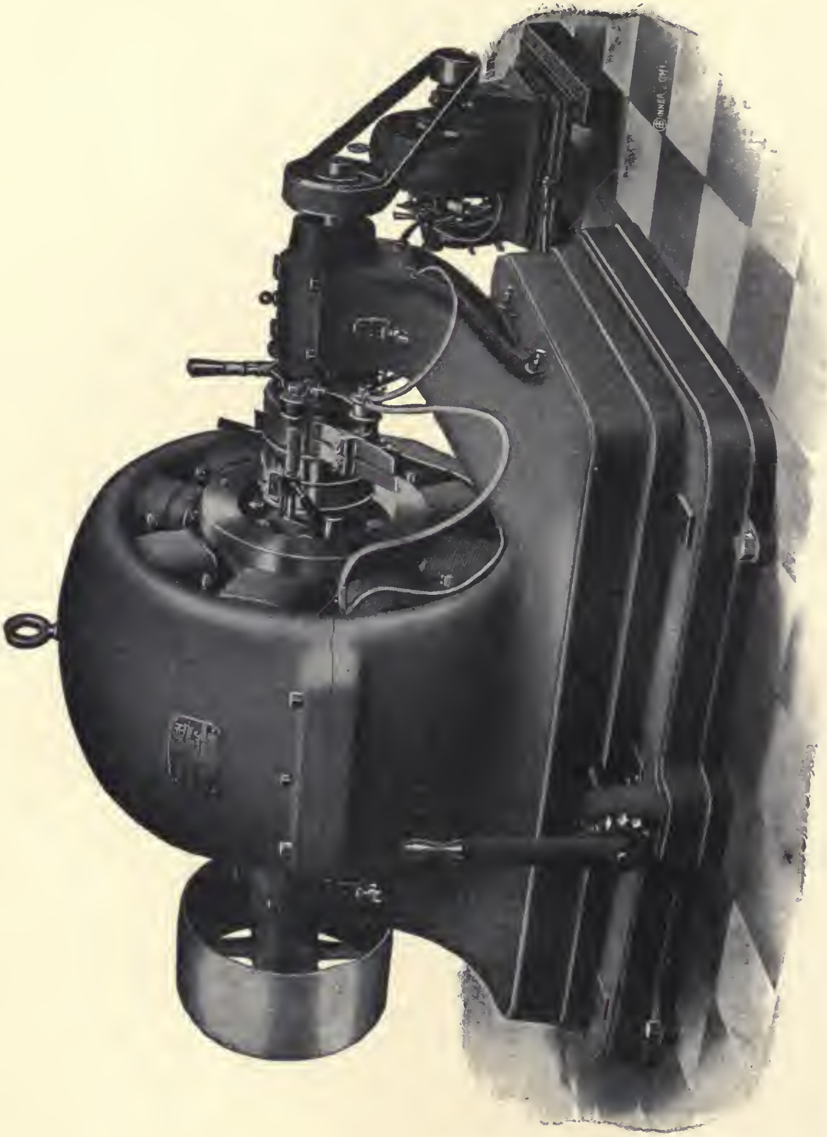


Fig 135

COMMERCIAL TYPES OF ALTERNATORS.

52. Alternators are of three types, differing in the means employed for causing the conductors to cut the magnetic flux from the field magnet. These types are:

1. Revolving-Armature Type.
2. Revolving-Field Type.
3. Inductor Type.

53. Revolving-Armature Alternators. In this type of alternator, the field magnet is stationary, while the armature is mounted on a shaft and is driven (by means of a belt or mechanical coupling) by the prime mover, which may be either a steam engine, a steam turbine, or a water wheel. The current induced in the armature conductors is delivered to the external circuit through collector rings on which brushes rub. The armature may be wound for a single-phase current (having two collector rings), for two-phase currents (having four collector rings), for three-phase currents (having three collector rings), etc. The revolving-armature type is used almost exclusively for alternators of small output and moderate voltage.

Fig. 133 shows a 90-kilowatt 1,100-volt 8-pole single-phase belt-driven alternator manufactured by the Fort Wayne Electric Company, of Fort Wayne, Indiana. It is designed to be driven at a speed of 900 revolutions per minute; hence the frequency of its electromotive force is $\frac{\frac{8}{2} \times 900}{60} = 60$ cycles per second. The figure shows the two collector rings adjacent to the armature, also the rectifying commutator with its brushes for supplying uni-directional current to the coarse wire coils of the composite field winding.

The exciter is a shunt-wound 4-pole 2-kilowatt direct-current generator running at a speed of 1,400 revolutions per minute. It is shown belted to a pulley on the alternator shaft. The current from this exciter is led to the fine wire coils of the composite field winding. Each field pole of the alternator is provided with two coils wound on one and the same spool—one of coarse wire, supplied with current from the rectifying commutator; and the other of fine wire, supplied with current from the exciter.

The field structure, base-plate, and pedestals are cast in one piece, and the whole machine rests upon a cast-iron sub-base. This sub-base is provided with slide rails along which the machine may be moved by means of a screw turned by a ratchet and lever, as shown—this for the purpose of adjusting the tension of the main driving belt. The field poles are "built up" of sheet-iron stampings and are held together by long bolts. These field poles are arranged in the mould in which the field frame is cast, and are thus cast-welded to the frame. The field coils are machine-wound on spools, with insulated copper wire, the coarse wire coils being wound on top of the fine wire coils. The field spools are held in position on the field poles by brass collars fixed to the outer ends of the poles.

The coarse wire coils, connected in series, are supplied with uni-directional current from the rectifying commutator; and the entire set is shunted with resistance consisting of a strip of German silver wound on an insulated form (Fig. 134), and mounted on an insulated block inside the hollow pedestal on the collector end of the machine.

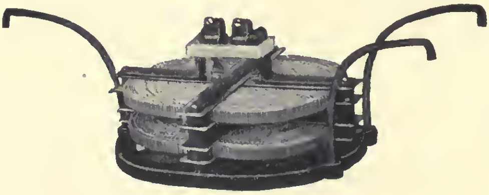


Fig. 134.

The armature is of the iron-clad ring type built up of small overlapping sheet-steel punchings, annealed and japanned to reduce the loss caused by hysteresis and eddy currents.

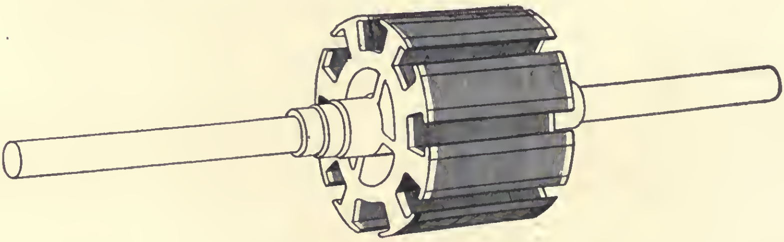


Fig. 135.

The armature winding is of the concentrated or uni-coil type. The coils are wound by hand directly on each armature tooth, insulated copper ribbon being used. Armature coils are generally wound on formers, and afterwards sprung into place in the slots on the armature core.

Figs. 135 and 136 show a Westinghouse single-phase uni-coil armature very much like the one used in the alternator shown in Fig 133. The coils of the Westinghouse alternator, however, are machine-wound on formers; and, after being taped, varnished, and baked, they are spread out slightly so as to pass over the teeth, and are forced into place in the deep slots, being securely held in place there by wooden wedges. Fig. 135 shows the core unwound, and Fig. 136 the method of placing coils in this type of machine. The armature teeth are T-shaped, and partially overhang the armature coils, thus protecting the coils from injury. There are, of course, the same number of armature teeth as field poles in the uni-coil armature. Thus Figs. 127 and 128 show an armature core for an eight-pole field.

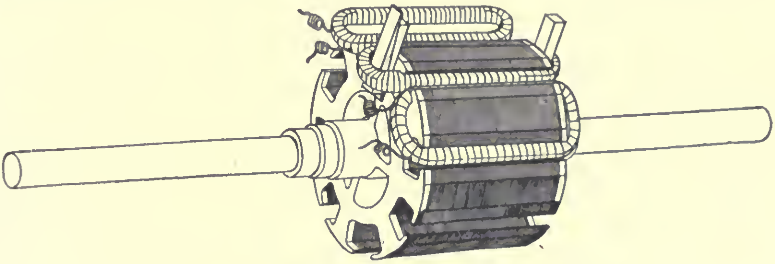


Fig. 136.

Fig. 137 shows the completed armature of which the core and coils are shown in Figs. 135 and 136. At the ends of the armature are two brass shields for protecting the ends of the armature coils. The ring-oiling, spherical-seated, self-aligning bearings are shown on the shaft in Fig. 137; and at the end of the shaft are shown the two collecting rings and the rectifying commutator.

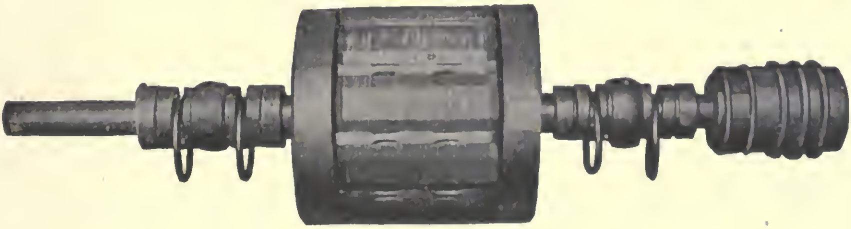


Fig. 137.

The wires leading to the collector rings and to the rectifying commutator are led through the shaft, which is made hollow.

Figs. 138 and 139 show a single-phase Westinghouse alternator armature with distributed winding. Three armature coils are shown in Fig. 138 separately and also grouped together. The manner of grouping shown is carried out when the armature coils are assembled on the armature core; and there are as many of these groups of armature coils as there are poles in the field. Fig. 139 shows the finished armature with end shields, collecting rings, and rectifying commutator.

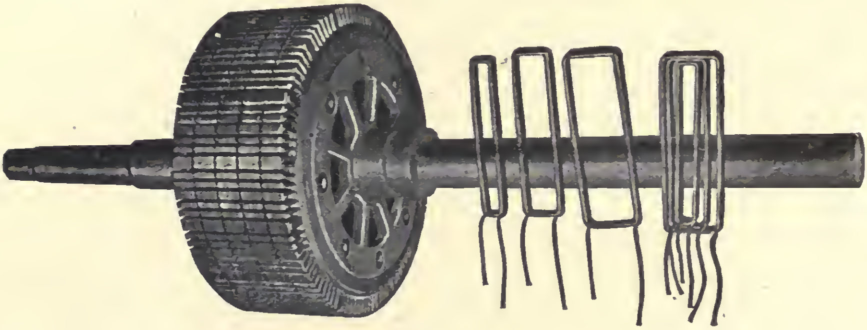


Fig. 138.

In assembling the stampings of an armature core a stiff, corrugated stamping (or its equivalent) is inserted at intervals between groups of the flat sheet-iron stampings, thus leaving radial air ducts from the inside to the outside of the armature core. These are known as **ventilating ducts**, and their object is to per-

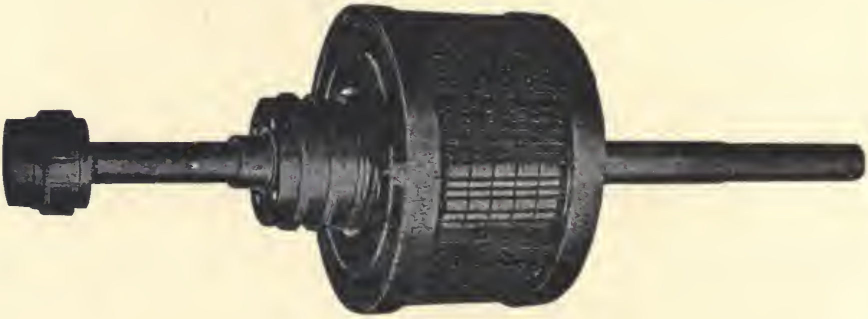
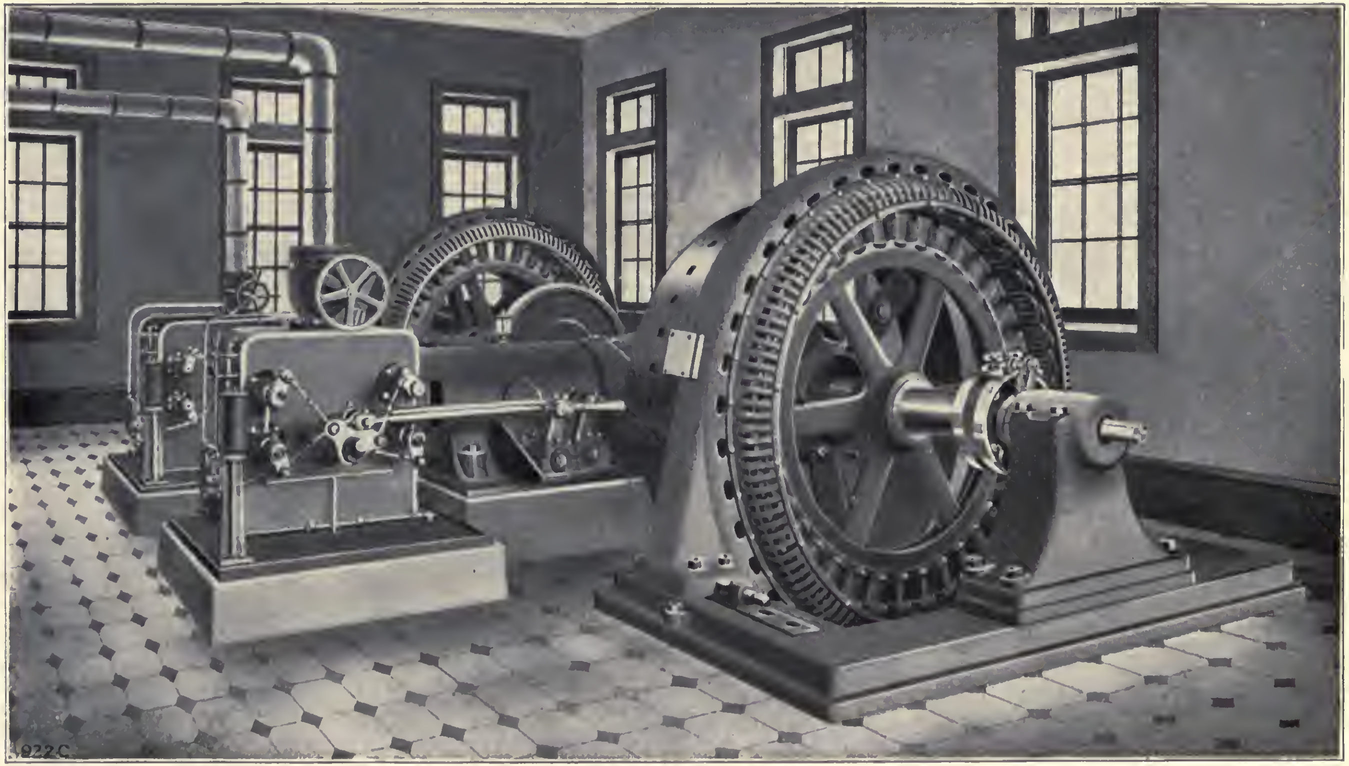


Fig. 139.



PLANT OF THE TIBBE ELECTRIC COMPANY, WASHINGTON, MO.

National Brake & Electric Co.

mit of a free circulation of cool air through the armature core and coils, thus preventing excessive rise of temperature. The motion of the armature causes air to be drawn in through the end shields to the interior of the armature, whence it is thrown out through the radial ducts, as in the case of a ventilating fan. Four of these spaces between stampings can be seen in Figs. 138 and 139; and the armature "spider" and end shields at each end, as shown, are provided with apertures for admitting cool air.

Fig. 140 shows the field structure of a Westinghouse 180-kilowatt alternator before the field coils have been placed upon it. The field poles (laminated) are shown projecting radially inwards from the cast-iron, ring-shaped yoke. The yoke is cast in two pieces, and the upper half is bolted to the lower half, as shown in the figure. The yoke is divided in this way in order that the upper half may be unbolted and may be lifted off by means of the eye-bolt on the top of the machine, thus giving easy access to the armature for inspection and repairs.

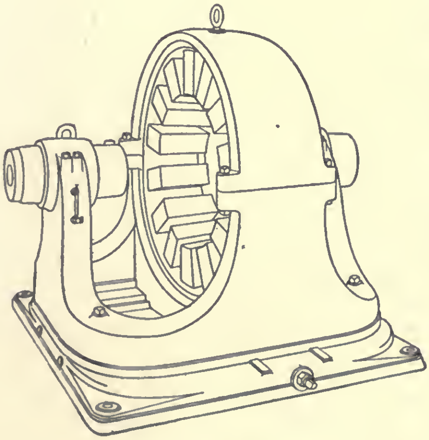


Fig. 140.

Fig. 141 shows a Westinghouse 375-kilowatt 2,000-volt two-phase revolving-armature alternator. The armature winding is continuous; taps from this winding are taken out to the collector rings spaced 90° apart for two-phase, and spaced 120° apart for three-phase. The large sizes are not provided with a composite field winding, but the small ones are usually so equipped.

54. Revolving-Field Alternators. In this type of alternator, the armature is stationary, and the armature windings are arranged in slots on the inner face of the armature structure, the latter forming a closed ring inside of which the multipolar field magnet revolves. The armature structure consists of an external frame of cast-iron or steel supported on a bed-plate. The armature core proper consists of a ring built up of relatively small stampings of sheet iron dovetailed into the external frame and pressed together between two flanges by bolts. The external frame in this type of alternator does not to any perceptible extent carry

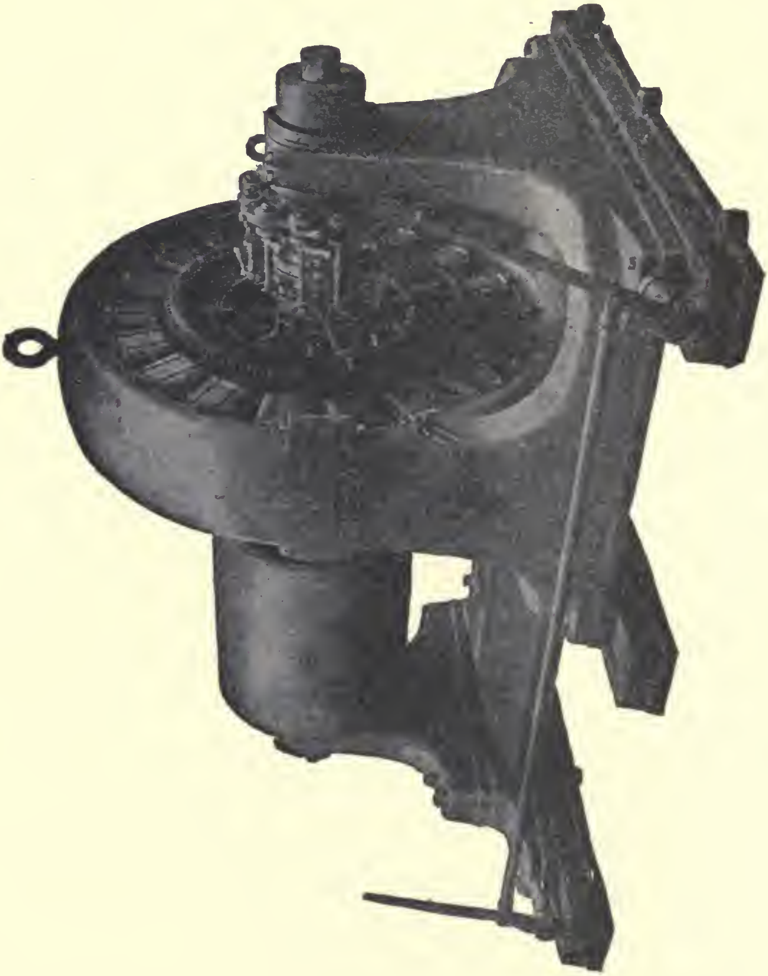


Fig. 141.

lines of force; that is, it does not form a part of the magnetic circuit, but serves only as a support for the laminated armature core. Fig. 142 shows the armature frame and core of a 100-kilowatt alternator of the Bullock Electric Manufacturing Company, of

Cincinnati, Ohio. The armature stampings are separated by corrugated plates (or their equivalent) in order to form ventilating ducts through the armature core. The fan action of the revolving field forces air into these ducts, whence it passes into the hollow casting and out through the holes shown in Fig. 142.

Fig. 143 shows an armature structure for a 600-kilowatt Bullock alternator, with a three-phase winding in place. This winding is distributed in two slots per pole per phase. The coils that constitute one of the phases are those of which the ends show most distinctly. The sides of the coils belonging to the other two phases lie in the remaining slots, four of which are surrounded by each pair of coils belonging to the first phase. The manner of connecting the coils belonging to each phase is explained in Article 51. This armature structure, Fig. 143, has two extensions cast as part of the frame, which are intended to rest upon a foundation on a level with the floor. The lower part of the ring is designed to extend below the level of the floor into a pit. In the same figure is shown also a metal shield screwed to the frame, and serving to protect the ends of the armature coils.

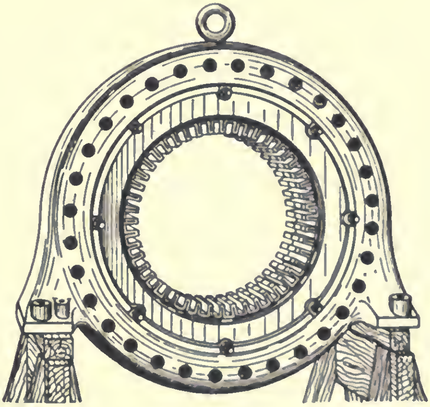


Fig. 142.

Fig. 144 shows a stationary armature structure for a three-phase alternator of the General Electric Company. It is wound for 12 poles, and is rated at 225 kilowatts at a speed of 400 revolutions per minute. In the figure the end guard-plate is removed, showing the ends of the windings; and showing also the three armature terminals, which are brought out through an insulated bushing screwed to the frame of the machine on the right.

The 36-pole field structure of a revolving field type of alternator of the General Electric Company is shown in Fig. 145. This field structure consists of laminated pole-pieces mounted on a cast-steel ring, and carried by a cast-iron spider. The pole-pieces

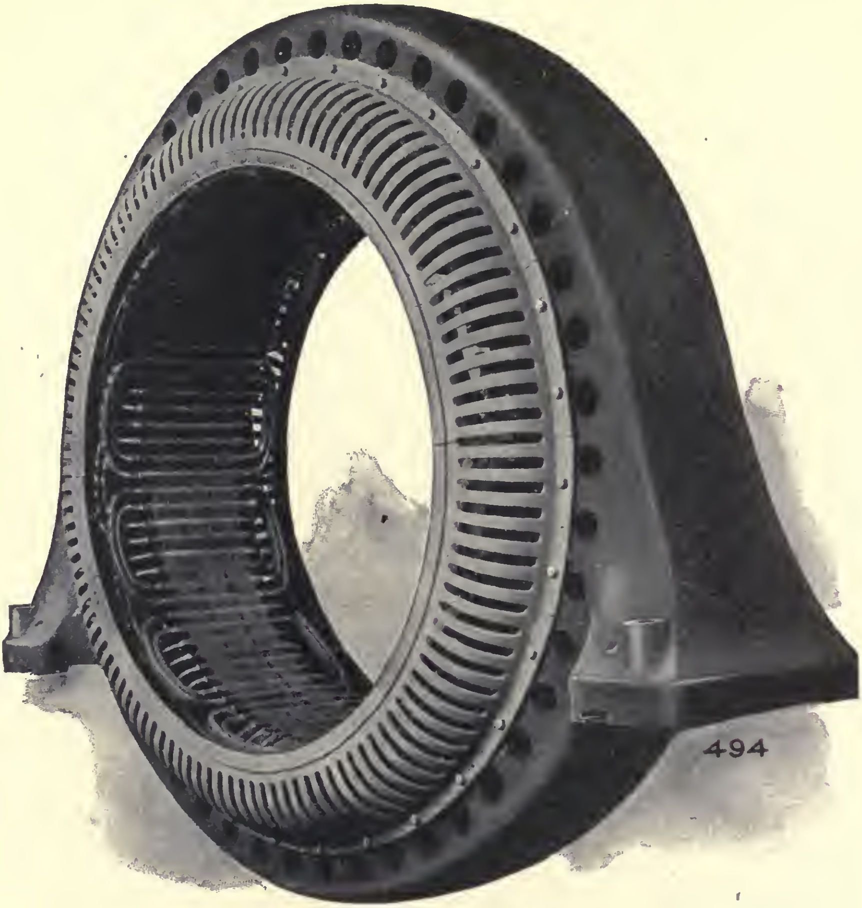


Fig. 143.

are built up of sheet iron, with a shoulder on the outer end so as to cover a wide polar arc and hold the field coils in place. The poles are attached to the steel ring by bolts passing through them (if the peripheral speed is low); or they are dovetailed into the ring, if subjected to high centrifugal stresses. Either method of construction permits easy removal of the pole-piece and field coils if necessary. One of these pole-pieces, with dovetail, is shown in Fig. 146.

Two methods of constructing field coils for revolving field machines are used by the General Electric Company. For smaller

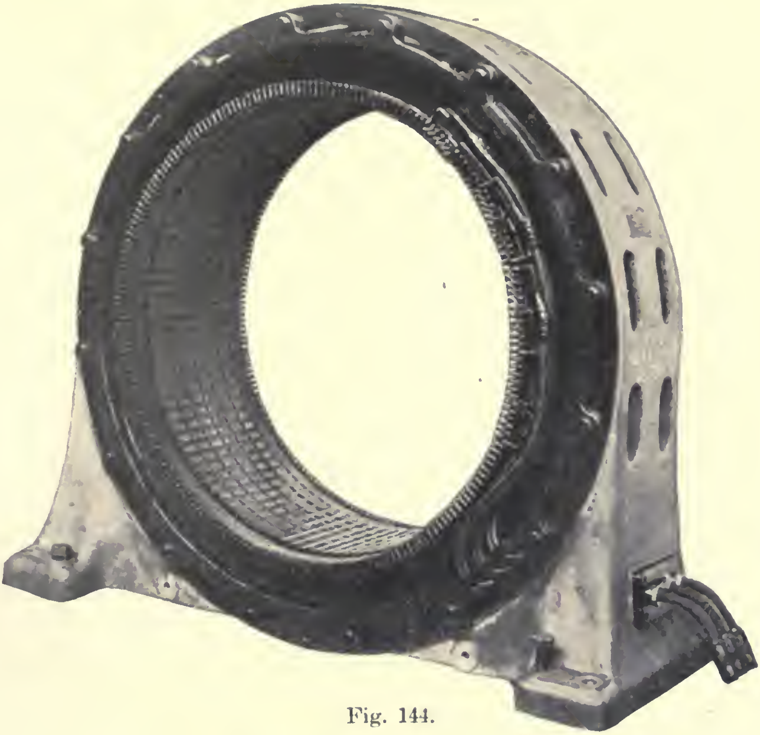


Fig. 144.

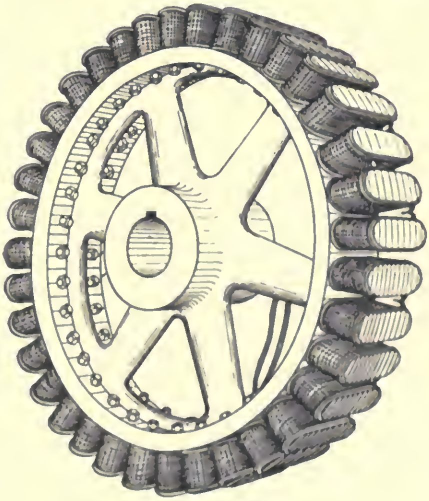


Fig. 145.

machines the wire is wound on spools which are slipped over the pole-pieces and held in place by the enlarged pole tips. In larger machines the field coils consist of a single strip of flat copper wound on edge, as shown in Fig. 146, so that the edge of every turn is exposed to the air to facilitate radiation, and hence cooling.

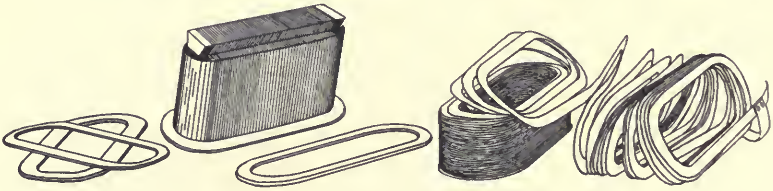
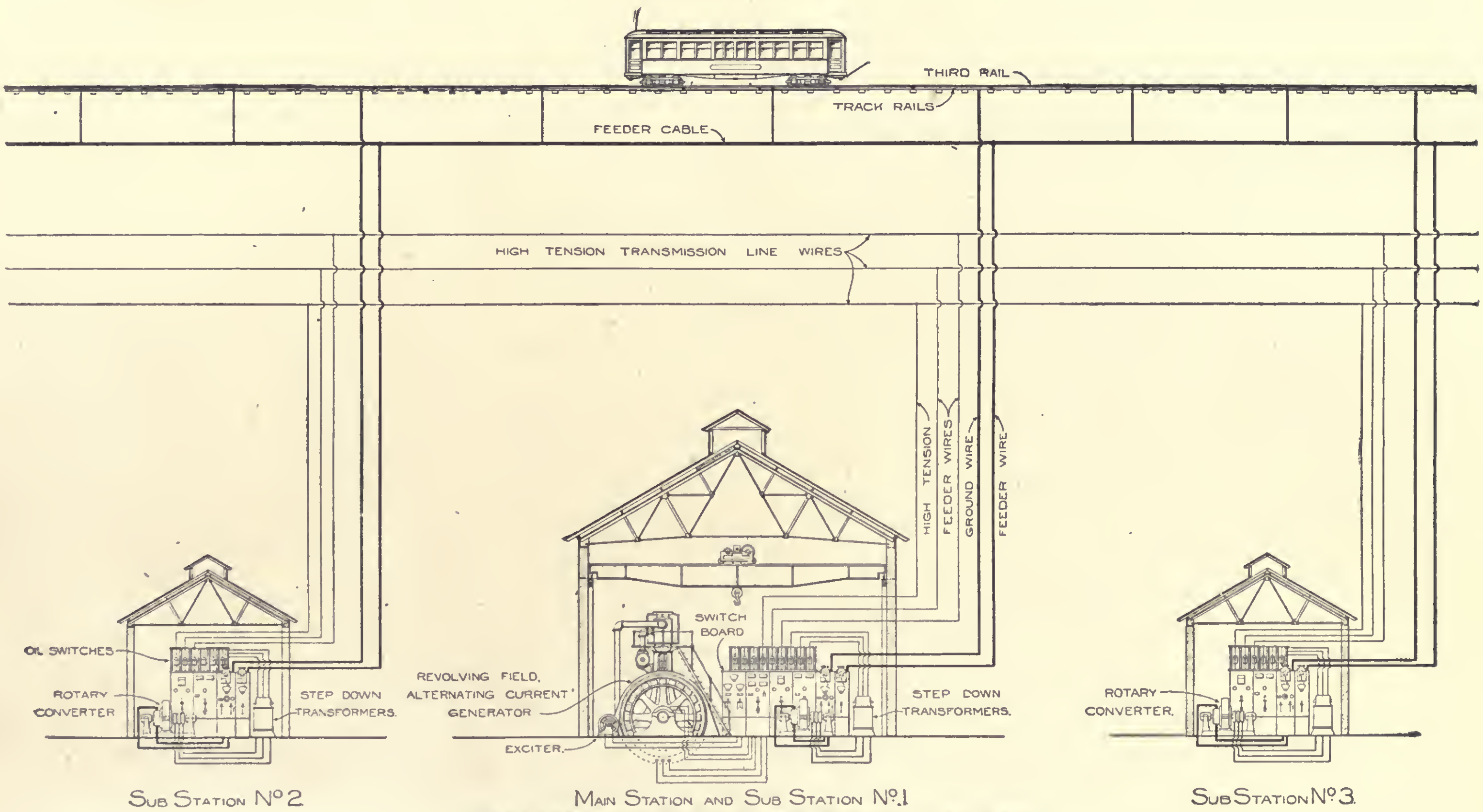


Fig. 146.

As the flat sides rest against each other, separated only by thin strips of paper for insulation, the entire coil forms a structure of great solidity.

The direct current for exciting the field magnet is carried in to the revolving field structure by means of brushes rubbing on collector rings to which are connected the terminals of the field coils. The latter are all connected in series.



THREE-PHASE DISTRIBUTION FOR ELECTRIC RAILWAYS.

General Electric Company.

ALTERNATING CURRENT MACHINERY.

PART III.

COMMERCIAL TYPES OF ALTERNATORS.

(Continued.)

Fig. 147 is a general view of an 8-pole 115-kilowatt two-phase belt-driven Bullock alternator of the revolving-field type. It is designed to give 2,200 volts at the armature terminals when driven at 900 revolutions per minute, giving a frequency of 60 cycles per second.

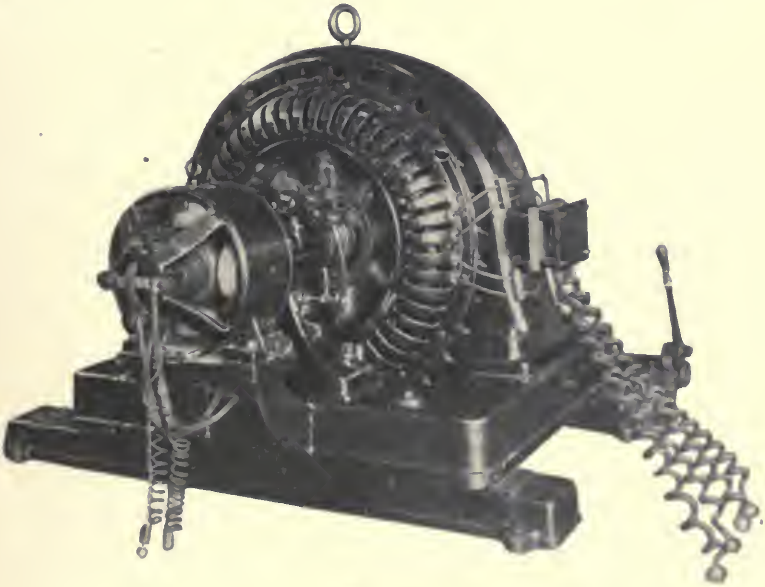


Fig. 147.

The exciter is a 4-pole direct-current generator with its armature mounted on the alternator shaft. The field frame of the exciter is bolted to an extension of the bedplate of the alternator. The four armature terminals are shown leading to a connection board bolted to the frame. From this connection board, four cables lead

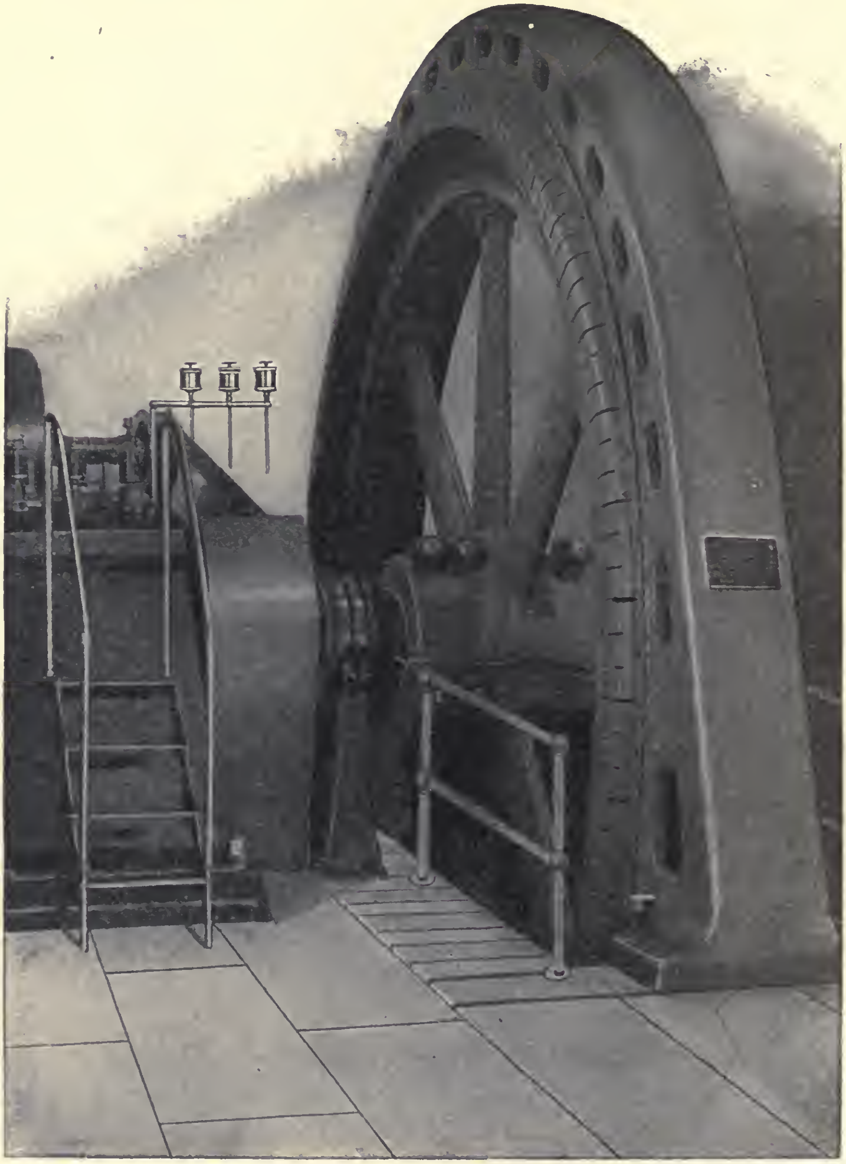


Fig. 148.

through insulated bushings under the floor, and thence are run in conduits to the switchboard (not shown).

Fig. 148 is a general view of a 48-pole 750-kilowatt direct-connected revolving field three-phase alternator built by the General Electric Company. It runs at a speed of 150 r.p.m., giving a frequency of 60 cycles per second and a full-load rated voltage of 2,300. The collecting rings and leads to the field winding are clearly shown in the figure. The armature frame is of cast-iron, of a strong box section, into which are dovetailed the iron punchings of the core. Ventilating spaces between the armature laminations provide for a circulation of air when the machine is running. The windings are set in slots and held in place by wedges over them.

Engine-driven alternators, especially in the largest sizes, are constructed with their field magnet poles mounted upon the rim of their fly-wheel structures. Such machines are called **fly-wheel alternators.** The alternators installed in the central power station of the Manhattan Railway Company, of New York City, by the Westinghouse Electric & Manufacturing Company, of Pittsburg, Pennsylvania, are good examples of fly-wheel alternators. These machines are rated at 5,000 kilowatts, and are guaranteed to deliver 7,500 kilowatts for two hours without excessive rise of temperature.

Fig. 149 is a general view of one of the eight generating units in the Manhattan power station. It consists of a vertical compound steam engine rated at 8,000 horse-power, with a 50 per cent overload capacity, direct-connected to a fly-wheel alternator.

The total height of one of these machines is 42 feet, the diameter of the revolving part is 32 feet, and the total weight is 185 tons. The combined fly-wheel and field magnet structure consists of a steel hub to which is fastened a built-up disc of steel, to serve, instead of spokes, for supporting the heavy rim. This rim consists, in the first place, of a number of cast-iron segments bolted to the steel disc, and having on their outer faces a series of dovetail channels into which the laminations forming the built-up field poles and connecting yokes (for completing the magnetic circuit) are dovetailed. Fig. 150 shows how these built-up field poles and connecting yokes are constructed, and how they are fastened to the cast-iron supporting structure. Three individual

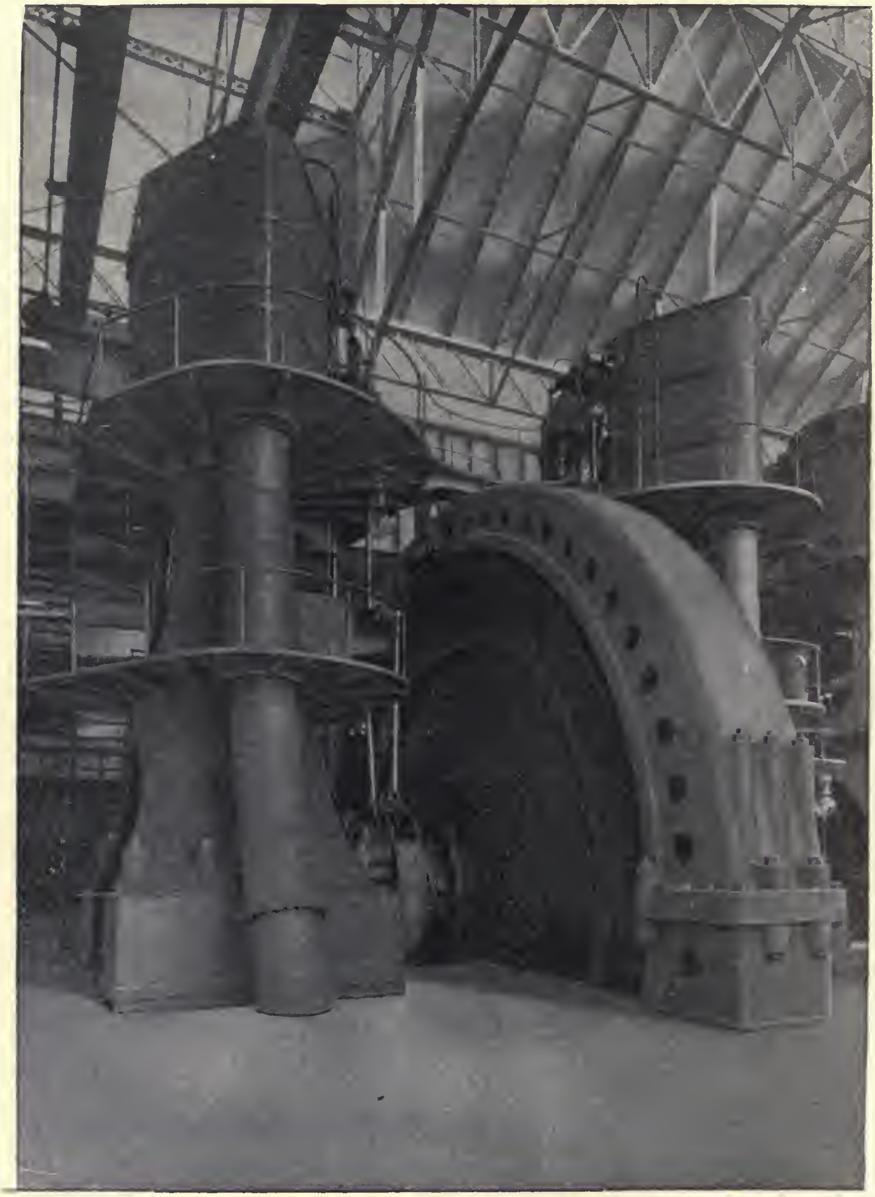


Fig. 149.

stampings are shown separate in the figure. Fig. 150 does not represent the revolving field structure of one of the Manhattan alternators described above, but the field structure of a similar but smaller machine.

In assembling the stampings that form the built-up structure of field poles and yokes, the stampings break joints in order to enable the structure to resist centrifugal force without bringing undue stress upon the central supporting structure. The stampings are perforated with a number of holes, as shown. These holes register in the built-up structure, and bolts are passed through them in order to clamp the laminations together. At intervals of about three inches, the laminations are separated by a corrugated lamination (or its equivalent), which serves to form ventilating ducts that extend inwardly to large openings in the cast-iron segments. These ventilating ducts in the revolving field, register or coincide with corresponding ducts in the external stationary armature.

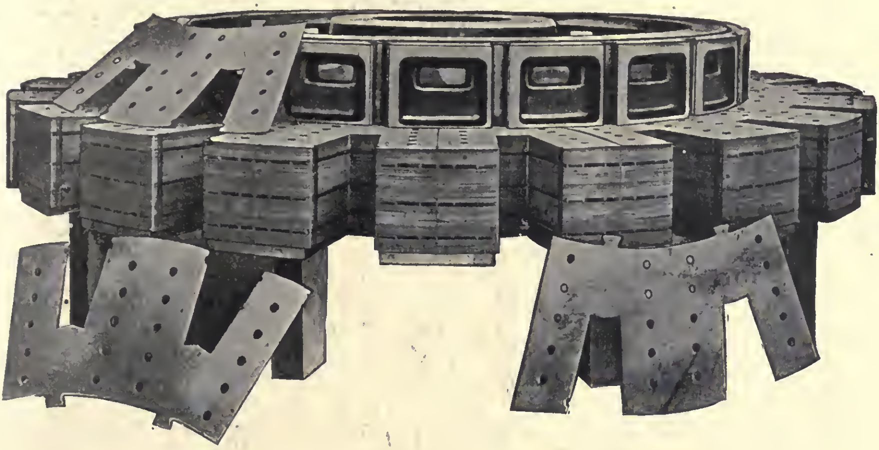


Fig. 150.

The field pole tips are beveled so as to produce a distribution of magnetic flux which will give approximately a sine-wave electromotive force at no load (under load conditions the wave would be somewhat distorted).

Fig. 151 shows a portion of the periphery of the rotating field structure of a Manhattan alternator with field coils in place.

The field coils are held in place by massive copper frames, which project under adjacent pole tips. These copper frames have also large external lips, which overhang the beveled edges of the poles. The frames, with their overhanging lips, act powerfully to retard any shifting of the field flux to and fro across the pole faces. Such a shifting of flux always accompanies the "hunting" action of alternators connected so as to be operated in parallel (as is the case with these Manhattan alternators); and the overhanging copper frames check this tendency to "hunt."

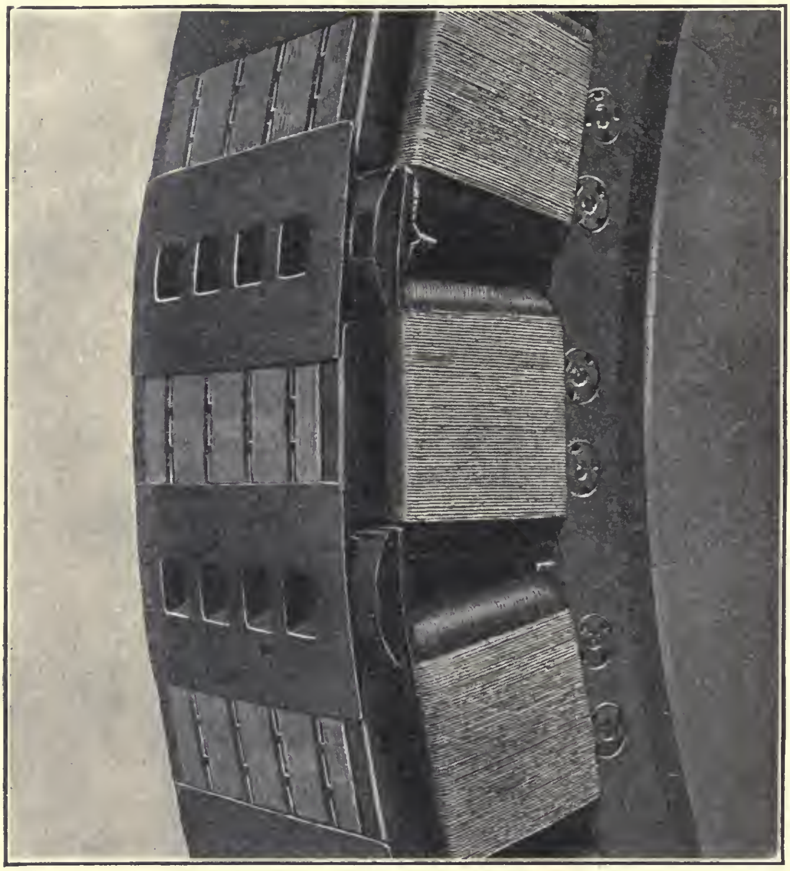


Fig. 151.

The speed of the Manhattan alternators is 75 r.p.m., which, with 40 poles, gives a frequency of 25 cycles per second. The armatures are wound with three phases, and they give 11,000 volts. The field requires 225 amperes at 200 volts when the alternator is delivering full-load current at 11,000 volts on a non-inductive load. About 15 per cent additional field current is required to give 11,000 volts when the alternator is run at full-load rated current, the power factor of the receiving circuits being 90 per cent. The full-load regulation of the machine is 6 per cent with non-inductive receiving circuits; that is, there is a 6 per cent rise of voltage when full non-inductive load is thrown off the machine. The efficiency of these alternators ranges from about 90 per cent at quarter load to about 96½ per cent at full load, when the receiving circuits are non-inductive.

55. Inductor Alternators. The inductor alternator is that type of alternator in which both the field winding and the armature (core and winding) are stationary, and in which the magnetic flux produced by the field winding is caused to move past the armature conductors by means of a rotating iron structure called the **inductor.** See Fig. 162.

Fig. 152 shows the stationary armature structure of a 150-kilowatt inductor alternator.

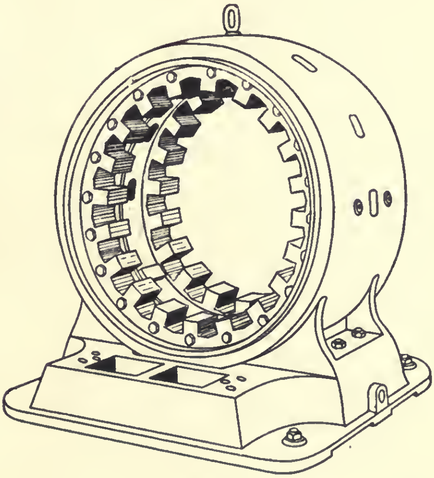


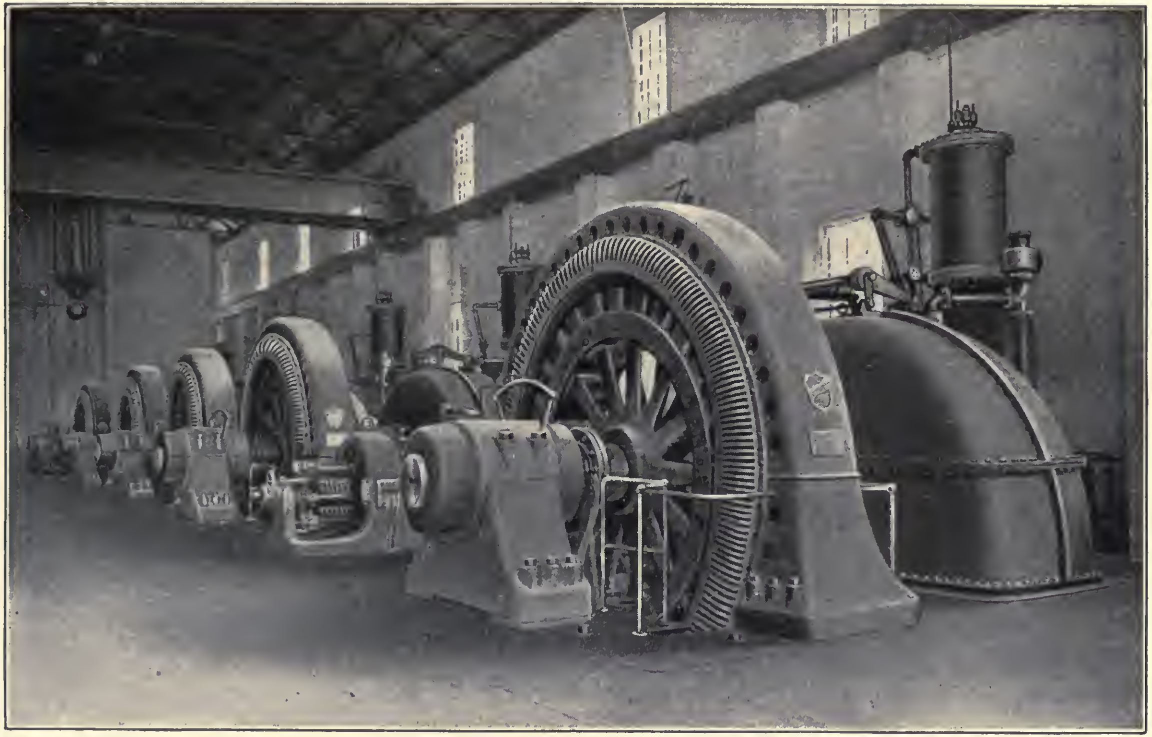
Fig. 152.

The armature is in some respects equivalent to two ordinary armatures side by side, as may be seen from the two rings or crowns of projecting teeth. Fig. 158 shows the large single-field spool with its supporting lugs. Fig. 160 shows the armature structure with armature windings and field spool in place, and Fig. 162 shows the rotating member or inductor. The field coil surrounds the narrow neck of the inductor between the two flux distributors. The magnetic flux produced by the field coil passes through the narrow neck of the inductor, Fig. 162, into an end-piece or distributor, around the periphery of which are a number of laminated polar projections from which the flux passes across one air gap into one crown of armature teeth and windings. Thence the flux passes through the cast-iron case of the armature structure to the other crown of armature teeth and windings, then across the other air gap into the polar projections on the other distributor, and finally back to the starting point. All the polar projections on one distributor are north poles, and all those on the other distributor are south poles.

Figs. 152 and 162 show a single-phase alternator. This machine with given windings may be altered from a single-phase machine to a two-phase machine by loosening one distributor, and turning it until its polar projections come opposite to the spaces between the polar projections on the other distributor. In this case the armature windings at one end of the armature structure constitute one phase, and the windings at the other end of the armature structure constitute the other phase.

Fig. 165 shows a belt-driven Stanley-Kelley-Chesney (S. K. C.) two-phase inductor alternator with its stationary armature structure separated so as to show the field coil and inductor. This belt-driven type is built in sizes from 125 K.W. to 225 K.W., running at speeds from 1,000 to 600 r.p.m., and wound to give any voltage up to 5,500 in the smaller sizes and up to 6,600 in the larger sizes. This type is provided with a vertically split armature structure with the armature halves arranged to slide on side tables cast in one piece with the bedplate. These armature halves can be slid apart by means of a screw operated by the upper hand wheel shown in the figure, thus giving access to the interior of the machine. The field coil is shown in Fig. 165, in place between the two flux distributors of the revolving member or inductor, one flux distributor being hidden from view in the figure. This field coil is bolted to the armature structure when the halves of the latter are brought together to form a continuous ring.

Fig. 166 illustrates a standard S. K. C. alternator arranged for direct connection to the driving engine. The inductor is arranged to slide along the shaft so as to give access to the interior of the machine. This type is also provided, if desired, with base, shaft, and bearings for direct coupling to water wheels and to types



FIVE 3,000 K. W. BULLOCK WATER-WHEEL TYPE GENERATORS

Bullock Electric Manufacturing Co.

of engines where the inductor cannot be mounted directly upon the engine shaft.

When this type is mounted directly upon an engine shaft, the manufacturers advise that the armature be not wound for higher voltages than 2,600 On the other hand, when this type is provided with its own base, shaft, and bearings, so that it can be insulated from the driving engine or water wheel, the armature can safely be wound to give voltages up to 12,000.

This direct-connected type is built in sizes from 600 K.W. to 2,000 K.W., running at speeds from 360 to 75 r.p.m. In the larger sizes it is not necessary to move the armature or inductor, in order to gain access to the armature coils.

The standard frequencies of S. K. C. alternators are 60, 66, and 133 cycles per second. The S. K. C. alternators are usually provided with a complete two-phase armature winding at each end of the machine, although in some cases each end of the armature is wound single-phase, and the polar projections of the inductor are "staggered" to give two phases, one at each end of the armature.

The relation between speed, frequency, and number of polar projections in the inductor alternator, is not the same as in the ordinary type of alternator with alternate north and south field poles. The electromotive force induced in a given coil of the armature of an inductor alternator passes through a complete cycle of values while the inductor is moving so as to replace a given polar projection by the next following polar projection; while in the ordinary type of alternator the electromotive force induced in an armature coil passes through half a complete cycle while the field magnet is moving so as to replace a given north pole by the next following south pole.

The armature windings of the inductor alternators shown are arranged exactly as they would be to adapt them to an ordinary revolving field magnet having twice the number of polar projections that the given inductors have. When two adjacent polar projections of the inductor are opposite two coils of the armature winding, there is an idle armature coil between the polar projections. Hence, on the whole, the armature windings are utilized only to half the extent that they are in an ordinary alternator. For this reason chiefly, the weight and cost of an inductor alternator of a given output are greater than the weight and cost of an alternator of the ordinary type.

56. Comparison of Types of Alternators. The revolving-armature type of alternator is limited to a general power and lighting distribution where only a moderate voltage is required. Machines of this type are comparatively cheap to build. They can be automatically compounded by the use of composite field windings without any complication of parts, which is not the case with the revolving-field or the inductor types of alternator. The efficiency of the revolving-armature type is somewhat higher than that of the other two types.

The revolving-armature type, on the other hand, is not suitable for generating either high or low voltages, on account of the difficulties of insulating the armature conductors and collecting rings in the first case (high voltage), and of collecting a large armature current in the second case (low voltage).

The stationary-armature (revolving-field) type can, on the contrary, be easily insulated to withstand a testing pressure of over 30,000 volts; and, as no collecting device is required, currents of large magnitude can be taken from the armature terminals without difficulty. Alternators with stationary armatures are now built to generate voltages up to 20,000; but it is doubtful whether on the whole, it is economical to build them for voltages greater than 10,000. Furthermore, a revolving field can be made stronger and more compact than a revolving armature, and therefore the revolving-field type of alternator is much the better suited to the high speeds employed in alternators driven by steam turbines. The combination of a steam turbine direct-connected to an alternator, is called a **turbo-generator.**

The great advantage of the inductor type of alternator is the absence of moving wire, and the consequent absence of all collecting rings and brushes, the cost of attendance being thus reduced to a minimum. On the other hand, close regulation is attainable only by increase of size, and consequent increase of cost.

57. Conditions Affecting Cost. The most important factor in determining the cost of an alternator for a given rated output, is its speed, inasmuch as a low-speed machine must be much larger than a high-speed machine of the same rated output. Belt-driven machines are always run at the highest speed compatible with safety to the alternator itself; while, on the other hand, the speed of a direct-connected alternator, being determined by the speed of the engine or water wheel, is usually less than is necessary for safe running. Therefore a belt-driven machine is usually cheaper than a direct-connected machine of the same rated output. Very large machines must be direct-connected, inasmuch as belt driving is out of the question for large machines on account of the excessive cost of very large belts, the great amount of floor space required, the power lost in the belt, the expense of attendance and maintenance, and the noise. Direct-connected alternators, especially machines of large rated output, are usually designed with the rotating member (armature or field) of large diameter, in order that the permissible speed of the alternator may be approximately the same as the proper speed of the driving engine or water wheel.

A second factor affecting cost is the voltage that is to be developed in the armature. A machine for high voltage must have a large number of armature conductors, and these conductors must be highly insulated—that is, the insulation must occupy a relatively large portion of the winding space in the slots. This requires a large machine for a given power output, on account of the space wasted, as it were, in insulation. To offset this disadvantage, a high-voltage alternator does not require the use of step-up transformers, the voltage generated in the alternator being suited for the transmission of power to moderate distances. That is, the extra cost of the alternator may be more than offset by the saving in the cost of the step-up transformers.

A third factor affecting cost is found in the requirements of close regulation and high efficiency. Thus an alternator of given power output may be made smaller in size, and therefore cheaper, if high efficiency and close regulation are not demanded. High efficiency and close regulation mean a liberal use of iron and copper in order to secure a minimum loss of power and electromotive force in a machine. Furthermore, the efficiency of a given size of alternator for given output may be increased at the expense of regulation, or *vice versa.*

A fourth factor affecting cost is the frequency required. With given speed an increase of frequency means an increase in the number of field poles and in the number of armature coils, and therefore an increase in the cost of construction. This element of cost is most prominent in very slow-speed direct-connected alternators. For example, a 133-cycle alternator, direct-connected to an engine running at 300 r.p.m., must have 52 poles to give the required frequency. To reduce the frequency to 40 cycles would require only 16 poles, with a corresponding reduction in the cost of the field magnet copper and of labor. On the other hand, lowering the frequency of an alternator, while keeping the speed constant, would require an increase in the useful flux per pole and a corresponding increase in the cross-sectional areas of the field yoke, the field poles, and the armature core. This would mean an increase in the amount of iron to be used in the machine. Iron, however, is cheap; and the extra cost of iron would be more than offset by the saving in copper and labor.

ALTERNATOR LOSSES, EFFICIENCIES, RATINGS, AND TESTS.

58. Losses of Power in an Alternator. The power lost in an alternator consists of the following parts:

(*a*) Loss due to brush, journal, and air friction. Air friction is usually called **windage.**

(*b*) Power consumed in heating the field windings by the exciting current.

(*c*) Power lost in heating the armature windings by the armature current or currents.

(*d*) Eddy current and hysteresis losses in all iron that is subject to variations of magnetization.

Friction and windage loss can be determined only by experiments upon the finished machine.

The power consumed in the field windings is RI^2, where R is the resistance of the field circuit, and I is the field current. The field rheostat is a part of the machine, and the losses occurring in it are a part of the machine losses. This same formula may be used to calculate power consumed in each field winding of a composite-field alternator.

The power lost in heating the armature windings is $RI^2 \times$ *the number of phases*, where R is the resistance of each phase, and I is the current in each phase.

The power lost by eddy currents and hysteresis may be approximately calculated by the method employed for the corresponding calculation in the case of a transformer.

59. Efficiency. The efficiency of an alternator is the ratio *output of power ÷ input of power*. Since the mechanical input of power is equal to the output of power plus all the losses of power, we have also:

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}}$$

At zero load (zero output), the efficiency of an alternator is therefore zero; the efficiency increases with increasing load, reaches a maximum, and falls off for large loads. An alternator may be designed to give its maximum efficiency at any prescribed fraction of full load. It is generally desirable to design the machine to give its maximum efficiency at approximately full load.

The efficiency of a large alternator at full load is usually greater than the efficiency of a small alternator. For example, the large alternators in the great power stations at Niagara Falls have efficiencies of over 98 per cent. A well-designed 50-kilowatt alternator has an efficiency of about 90 per cent.

60. Practical and Ultimate Limits of Output. The dotted curve, Fig. 153, is the characteristic curve of a given alternator. This curve shows the relation between the current output (plotted as abscissas) and the electromotive force between the collecting rings (plotted as ordinates, using scale to the left), the field excitation being kept constant. The ordinates of the full-line curve (scale shown to the right in the figure) represent the power outputs (in kilowatts) corresponding to the different current outputs (receiving circuit non-inductive). The maximum output

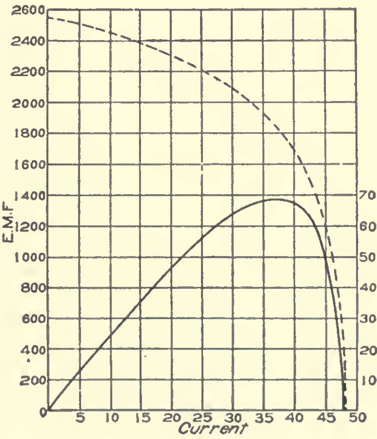


Fig. 153.

of the alternator, in this case, is 68 kilowatts when the current output is 38 amperes. In practice the allowable power output of an alternator is limited to a smaller value than this maximum output by one or the other of the following considerations:

(*a*) Electric lighting and power service usually demands an approximately constant electromotive force; and it is not permissible to take from an alternator a current so large as greatly to reduce its electromotive force. This difficulty may be largely overcome by providing for an increase of field excitation of the alternator with increase of load, as is done in the alternator with a composite field winding.

(*b*) The current delivered by an alternator generates heat in the armature of the alternator; and the temperature of the armature rises until it radiates heat as fast as heat is generated in it by the current. Excessive heating of the armature endangers the insulation of the windings; and it is not permissible to take from an alternator a current so large as to heat its armature more than 40° or 50° C above the temperature of the surrounding air. This heating effect of the armature currents usually fixes the allowable output of an alternator, except in those rare cases where extreme steadiness of electromotive force is required, or where the alternator does not have composite field excitation.

Influence of Inductance upon Output. Alternators are rated according to the power they can deliver steadily to a non-inductive receiving circuit without overheating. The amount of power which an alternator can satisfactorily deliver to an inductive receiving circuit is less than that which it can deliver to a non-inductive receiving circuit, because of the phase difference of electromotive force and current. The cosine of the angle of phase difference (cos θ) is called the "power factor" of the receiving circuit, as before pointed out. The power factor of lighting circuits is very nearly unity if the transformers are all operating at approximately full load.

A transformer having its primary coil connected to alternating current mains, but furnishing no current from its secondary coil, has a power factor of approximately 0.7. The power factor increases with the secondary lamp load, until, in the neighborhood of full load, the power factor is nearly unity.

Induction motors, like transformers, have a maximum power factor at full load. The power factor of induction motors, even at full load, rarely exceeds 0.9; under partial loads it falls to 0.7 or even less.

A mixed load consisting of transformers and induction motors more or less fully loaded, has an average power factor of from 0.8 to 0.85.

61. Rating and Overload Capacities. Previous to the definite recommendations of the American Institute of Electrical Engineers in the matter of overload capacities as given below, there were great differences among different manufacturers in the rating of alternators. Thus one maker might have sold a certain alternator as a 50-kilowatt alternator, although the machine might have been capable of delivering 50 per cent overload (or 75 kilowatts) for several hours without dangerous rise of temperature; whereas another maker might have sold an exactly similar machine as a 75-kilowatt alternator.

As an illustration of the difference of permissible rating of a given alternator according to conditions of service, the following is taken from the practice of one of the large American manufacturing companies.

A certain alternator has twenty poles, and runs at 150 r.p.m. When this machine is rated at 300 kilowatts, its maximum rise of temperature will not exceed 35°C (by thermometer) when it is operated continuously with non-inductive full load; its maximum rise of temperature will not exceed 55°C when it is run for two hours at 50 per cent overload non-inductive. Its full-load regulation will be 6 per cent with non-inductive load, and 18 per cent with 80 per cent power factor.

When this same machine is rated at 360 kilowatts, its maximum rise of temperature will not exceed 40°C (by thermometer) when it is operated continuously with non-inductive full load; its maximum rise of temperature will not exceed 55°C when it is run for two hours at 25 per cent overload non-inductive. Its full load regulation will be 8 per cent with non-inductive load, and 22 per cent with 80 per cent power factor.

In general the rated power output of any alternator may be 20 per cent higher with a permissible rise of temperature of 40°C and a regulation of 8 per cent on non-inductive full load, than with a permissible rise of temperature of 35°C and a regulation of 6 per cent on non-inductive full load.

61a. American Institute Rules on Ratings and Overload Capacities. In order to establish a definite and uniform basis for rating alternators and for guaranteeing their performance in service under normal full load as well as overload, the following rules have been adopted by the American Institute of Electrical

Engineers. The numbers in parentheses are the paragraph numbers of the revised report of the Institute Committee on Standardization:

"(75) Both electrical and mechanical power should be expressed in kilowatts, except when otherwise specified. Alternating-current apparatus should be rated in kilowatts on the basis of non-inductive condition, *i. e.*, with the current in phase with the terminal voltage.

"(76) Thus the electric power generated by an alternating-current apparatus equals its rating only at non-inductive load, that is, when the current is in phase with the terminal voltage.

"(77) Apparent power should be expressed in kilovolt-amperes as distinguished from real power in kilowatts.

"(78) If a power-factor other than 100 per cent is specified, the rating should be expressed in kilovolt-amperes and power factor at full load.

"(79) The full-load current of an electric generator is that current which, with the rated full-load terminal voltage, gives the rated kilowatts, but in alternating-current apparatus only at non-inductive load.

"(80) Thus, in machines in which the full-load voltage differs from the no-load voltage, the full-load current should refer to the former.

"If P = rating of an electric generator, and E = full-load terminal voltage, the full-load current is:

$$I = \frac{P}{E} \text{ in a continuous current machine or single-phase alternator.}$$

$$I = \frac{P}{E\sqrt{3}} \text{ in a three-phase alternator.}$$

$$I = \frac{P}{2E} \text{ in a quarter-phase alternator.}$$

"(89) All guarantees on heating, regulation, sparking, etc., should apply to the rated load, except where expressly specified otherwise; and in alternating-current apparatus, to the current in phase with the terminal e.m.f., except where a phase displacement is inherent in the apparatus.

"(90) All apparatus should be able to carry the overload specified in Section 92, without self-destruction by heating, sparking, mechanical weakness, etc., and with an increase in temperature elevation not exceeding 15° C above those specified for full loads, the overload being applied after the apparatus has acquired the temperature corresponding to full-load continuous operation.

"(91) Overload guarantees should refer to normal conditions of operation regarding speed, frequency, voltage, etc.; and to non-inductive conditions in alternating apparatus, except where a phase displacement is inherent in the apparatus.

"(92) The following overload capacities are recommended:

"1st. In direct-current generators and alternating-current generators—25 per cent for two hours.

"2d. In direct-current motors, induction motors, and synchronous motors, not including railway motors and other apparatus intended for intermittent service—25 per cent for two hours, and 50 per cent for one minute, for momentary overload capacity.

"3d. Synchronous converters—50 per cent for one-half hour.

"4th. Transformers—25 per cent for two hours. Except in transformers connected to apparatus for which a different overload is guaranteed, in which case the same guarantees shall apply for the transformers as for the apparatus connected thereto.

"5th. Exciters of alternators and other synchronous machines—10 per cent more overload than is required for the excitation of the synchronous machine at its guaranteed overload, and for the same period of time.

"7th. All exciters of alternating-current, single-phase or polyphase generators should be able to give, at constant speed, sufficient voltage to excite the alternator, at the rated speed, to the full-load terminal voltage at the rated output in kilovolt-amperes and with 50 per cent power factor."

61b. Alternating-Current Testing in General. In the commercial testing of alternating-current apparatus, as in that of direct-current apparatus, the object of the tests is to determine the performance of the apparatus under normal working conditions. Care must be taken, therefore, to carry out each test under the normal working conditions with respect to speed, voltage, frequency, etc. Errors of observation may be greatly reduced by taking a series of observations instead of a single observation or a single set of observations. The observations of this series should be plotted point for point, and a smooth curve drawn through the points in such a way that the points will be equally distributed on both sides of the curve.

Different classes of apparatus require different tests; moreover, the same test may be performed differently on different kinds of machines. For the sake of convenience the different classes of apparatus treated will be taken up in the following order:

(1) Alternating current generators; (2) Synchronous motors; (3) Transformers; (4) Rotary converters; (5) Induction motors.

Every piece of electrical apparatus must satisfy two vital requirements, namely:

(*a*) It must have insulation of sufficient strength to stand safely the voltage at which it is intended to be operated.

(*b*) It must not overheat under normal working conditions.

Faulty insulation must be carefully guarded against, since, by the breaking down of the insulation, the apparatus may be put out of service. In the case of transformers for lighting service, a breakdown of the insulation between the primary and secondary coils endangers the life of persons coming in contact with fixtures on the secondary circuit. Overheating a machine causes a gradual deterioration of the insulation, which may finally result in a complete breakdown of the apparatus. Overheating must, therefore, be avoided.

61c. Insulation Testing. There are three distinct kinds of insulation tests:

(*a*) The determination of the electrical resistance of the insulation in ohms.

(*b*) The subjecting of the insulation of an apparatus to a prescribed voltage in excess of the rated voltage of the apparatus. This test is intended to insure that the apparatus will operate safely at its rated voltage. It is frequently called the "test of dielectric strength".

(*c*) The subjecting of the insulation to a voltage which is increased until the insulation is punctured or breaks down. This is called the "break-down test".

(*a*) The **insulation resistance test,** or in other words, the determination, in ohms, of the resistance of an insulation, is usually made by measuring with a sensitive galvanometer the very small current that is forced through the insulation by a known direct or steady electromotive force. The value of the resistance is equal to the electromotive force divided by the current.

The resistance in ohms of the insulation is of only secondary importance as compared with the dielectric strength or the resistance to rupture by high voltage. Insulation resistance tests should, if possible, be made using the electromotive force for which the apparatus is designed.

The insulation resistance of the complete apparatus should be such that the rated voltage of the apparatus will not send more than $\frac{1}{1000000}$ of the full-load current, at the rated terminal voltage, through the insulation.

(*b*) The **test of dielectric strength** is usually made as follows: The terminals of the secondary coil of a step-up "high potential" transformer are connected to the terminals of a spark gauge and to the terminals of the insulation to be tested, as shown in Fig. 154. The figure shows that the apparatus under test and the spark gap are connected in parallel between the terminals of the secondary (high-voltage) coil of the testing transformer. The spark gauge (see article 32) is set at a sparking distance corresponding to the voltage to be used in the test; and the voltage is increased by adjusting the water rheostat in series with the primary (low-voltage) coil of the transformer, until either the insulation is punctured or the desired voltage is reached, as will be indicated by the sparking across the gap between the needle points.

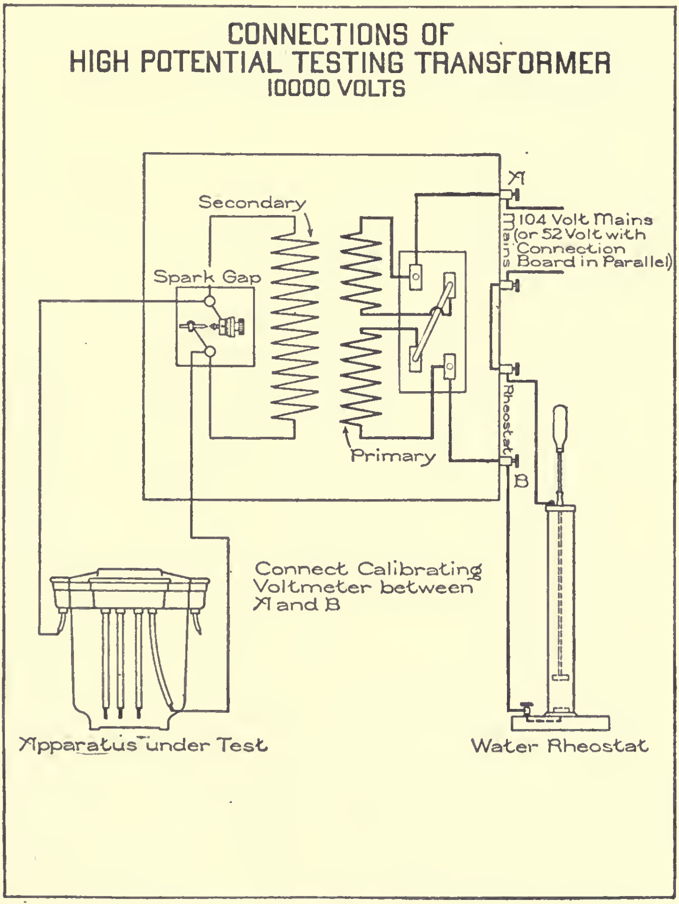
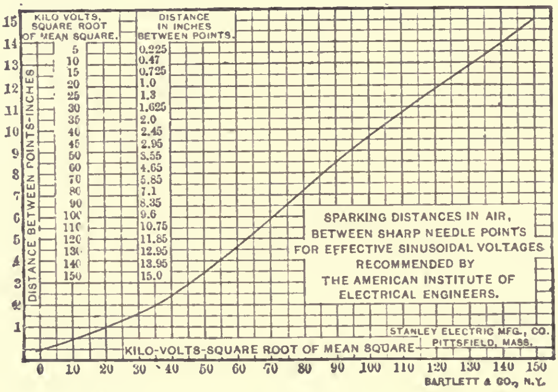

CONNECTIONS OF
HIGH POTENTIAL TESTING TRANSFORMER
10000 VOLTS
Secondary
Spark Gap
Primary
A
B
Mains
104 Volt Mains (or 52 Volt with Connection Board in Parallel)
Rheostat
Connect Calibrating Voltmeter between A and B
Apparatus under Test
Water Rheostat

Fig. 154.

Fig. 154 shows the electrical connections for carrying out a test of dielectric strength on a certain commercial transformer, marked in the figure "apparatus under test". It will be seen that one terminal of the high-voltage coil of the testing transformer is connected to one terminal of the primary coil (at the left) of the transformer under test, and the other terminal of the high-voltage coil of the testing transformer is connected to one of the four terminals of the secondary coils of the transformer under test. The high voltage is therefore applied to the insulation between the primary and secondary coils of the transformer under test.

Tests of dielectric strength are made with voltages ranging from $1\frac{1}{2}$ to 10 times the rated terminal voltage of a piece of apparatus, according to the rated voltage and output of the apparatus.


KILO VOLTS, SQUARE ROOT OF MEAN SQUARE.	DISTANCE IN INCHES BETWEEN POINTS.
5	0.225
10	0.47
15	0.725
20	1.0
25	1.3
30	1.625
35	2.0
40	2.45
45	2.95
50	3.55
60	4.65
70	5.85
80	7.1
90	8.35
100	9.6
110	10.75
120	11.85
130	12.95
140	13.95
150	15.0

SPARKING DISTANCES IN AIR, BETWEEN SHARP NEEDLE POINTS FOR EFFECTIVE SINUSOIDAL VOLTAGES RECOMMENDED BY THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Fig. 155.

For example, a transformer of any output whose rated terminal voltage is 20,000 would, according to the recommendations of the American Institute of Electrical Engineers, be tested with 30,000 volts, whereas a 1,000-volt transformer would be tested with 3,500 volts. An induction motor under 10 H.P. rated at 110 volts would be tested with 1,000 volts.

(*c*) The **break-down test** is frequently applied in the testing of small samples of insulating material. For example, a sheet of fuller board, mica-canvas, oiled linen or cloth, would be clamped between sheets of metal connected to the terminals of the high-voltage coil of the testing transformer, and the voltage would be increased until the insulation was punctured, the voltage producing puncture being recorded. A basis is thus obtained for the acceptance or rejection by the purchaser of a lot of insulating material.

The following table gives, in inches and in centimeters, the sparking distances in air between opposed sharp needle-points, corresponding to various *effective sinusoidal* voltages. The voltages are expressed in kilovolts (1 kilovolt = 1,000 volts). Fig. 155 is a curve plotted from the data given in the table and shows graphically the relation between sparking distance and voltage. The voltage corresponding to a given sparking distance varies greatly with the sharpness of the needle-points, and with the shape of the electromotive force wave.

TABLE III.

Sparking Distances for Various Voltages.

Kilovolts. Sq. Root of Mean Square.	Distance.		Kilovolts. Sq. Root of Mean Square.	Distance.	
	Inches.	Cms.		Inches.	Cms.
5	0.225	0.57	60	4.65	11.8
10	0.47	1.19	70	5.85	14.9
15	0.725	1.84	80	7 1	18.0
20	1.0	2.54	90	8.35	21.2
25	1.3	3.3	100	9.6	24.4
30	1.625	4.1	110	10.75	27.3
35	2.0	5.1	120	11.85	30.1
40	2.45	6.2	130	12.95	32.9
45	2.95	7.5	140	13.95	35.4
50	3.55	9.0	150	15.0	38.1

Sometimes the value of the voltage applied to the apparatus is not measured by the spark gauge, but is inferred from the reading of a low-reading voltmeter connected between the points A and B in Fig. 154. Thus, if there are 100 times as many turns of wire in the secondary (high-voltage) coil of the testing transformer as in the primary coil, then the readings of the voltmeter connected as specified must be multiplied by 100.

61d. Characteristic Curves and Tests — Saturation Curve. The saturation curve of a generator shows the relation between the volts generated in the armature and the amperes of field currrent (or ampere-turns of the field), for a constant armature current. The armature current may be zero, in which case the curve is called **no-load saturation curve,** or sometimes the **open-circuit characteristic curve.** A saturation curve may be taken with full-load current in the armature; but this is rarely done, except in alternators of comparatively small output. If a full-load saturation curve is desired, it can be approximately calculated from the no-load saturation curve and the curve for synchronous impedance, as will be explained later.

The diagram of connections for determining the no-load saturation curve is shown in Fig. 156. The alternator is represented as a three-phase machine of the revolving-field type (armature is stationary). The field winding is connected through slip-rings *d* and *e*, and brushes *f* and *g*, to an ammeter A, and through an adjustable resistance *r*, to the exciter or other direct-current source. A voltmeter V_1 is connected across the field-winding terminals to measure the voltage applied to the field winding. The voltmeter V_2, for measuring the voltage generated by the machine, is connected directly to two of the armature terminals, *a* and *c*, in the case of a low-voltage machine. If the voltage generated is greater than the capacity of the voltmeter, a multiplying coil or a step-down potential transformer may be used to reduce the electromotive force to be measured. For very high voltages a potential transformer must be used.

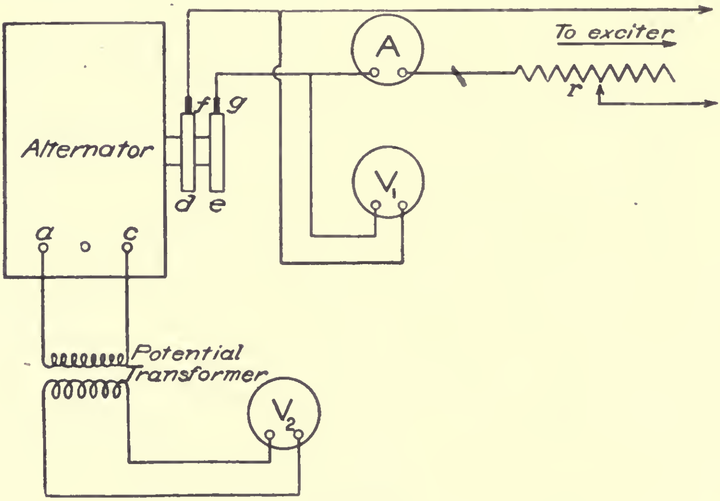


Fig. 156.

A series of observations of the electromotive force between the terminals of one of the phases, such as *a* and *c*, is made for different values of the field current. Eight or nine points along the curve are usually sufficient, the series extending from zero electromotive force to about fifty per cent above normal rated voltage. The points should be taken more closely together in the vicinity of normal voltage than at other portions of the curve Care must

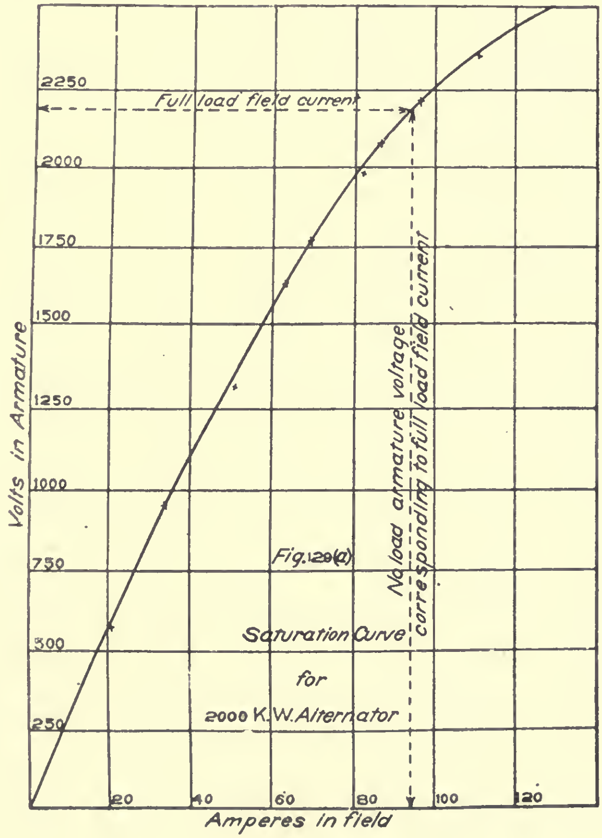


Fig. 157.

be taken that the generator is run at its rated speed, and this speed must be kept constant. Deviations from constant speed may be most easily detected by the use of a tachometer.

If the machine is two-phase or three-phase, the voltmeter may be connected to any one phase throughout a complete series of observations. The voltage of all the phases should be observed for normal full-load excitation by connecting the voltmeter to each phase successively, keeping the field current constant at normal voltage. This is done in order to see how closely the voltage of the different phases agree.

The observations required for the determination of the saturation curve are the following:

Volts at Armature Terminals, V_2.	Amperes in Field, A.	Volts at Field Terminals, V_1.	Speed.

Fig. 157 shows a saturation curve taken from a 2,000-kilowatt three-phase alternator of the revolving-field type, having 16 poles, and generating 2,000 volts, and 576 amperes per phase, when run at 300 revolutions per minute.

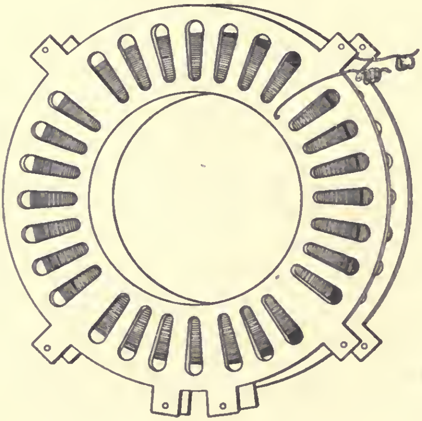


Fig. 158.

Fig. 159 gives a number of curves for a two-phase 135-kilowatt 2,400-volt 60-cycle S. K. C. inductor alternator. In particular, the no-load saturation curve is shown giving the relation between the field current and the voltage between armature terminals of one phase. This curve shows that nearly 7 amperes of field current is required to give rated voltage (namely 2,400) at no-load. The field current required to give voltage at full non-inductive load is 8.8 amperes, as is explained in article 64 on regulation. From the saturation curve it is evident that this full-load field current will produce about 2,625 volts at no load.

62. Synchronous Impedance.* The synchronous-impedance curve shows the relation between armature voltage and armature current, the armature being short-circuited so that the only condition that limits the current for a given voltage generated is the synchronous impedance of the armature. This is materially different from the impedance of the armature when the machine is standing still.

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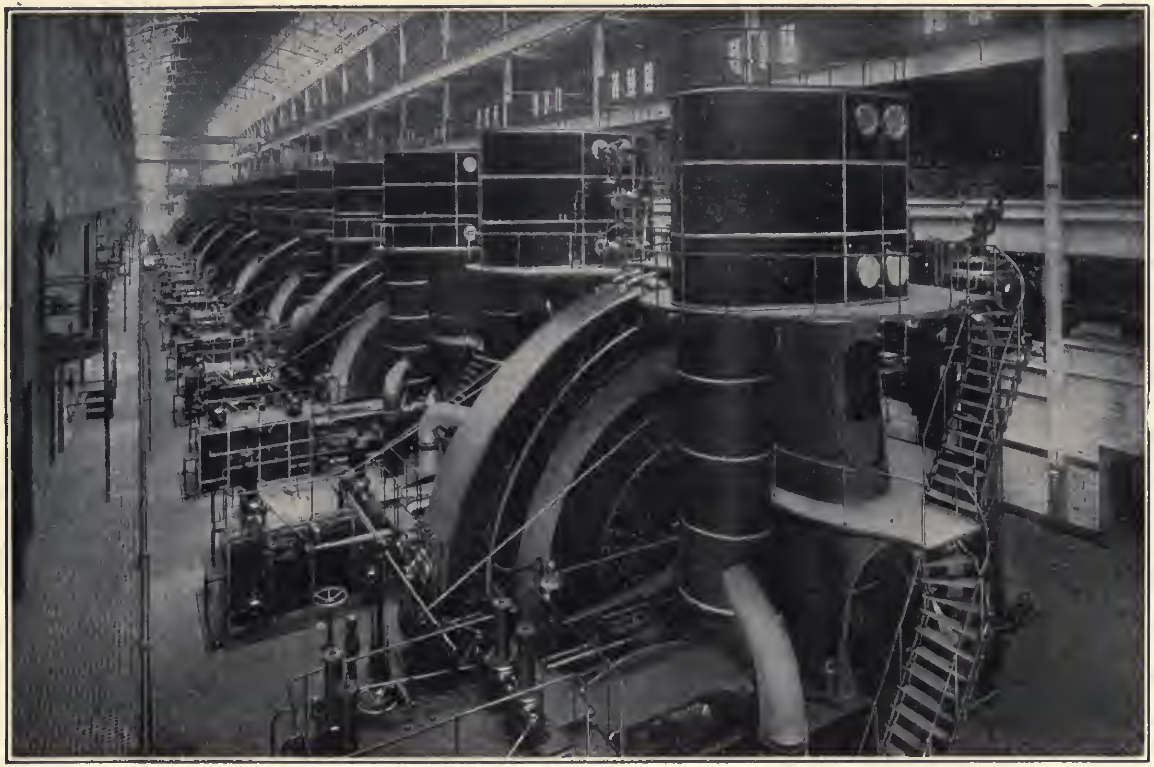
*See Article 41.



5,000 K. W., 11,000 VOLT, THREE-PHASE, ENGINE TYPE A. C. GENERATORS—59th STREET STATION
INTERBOROUGH RAPID TRANSIT COMPANY, NEW YORK, N. Y.

Westinghouse Electric & Manufacturing Co.

The connections for this test are similar to those for the saturation curve, except that the voltmeter (or potential transformer) connected to the armature is replaced by an ammeter. If the current is beyond the capacity of the ammeters at hand, a current transformer may be connected in the place of the ammeter, and the ammeter connected to its secondary.

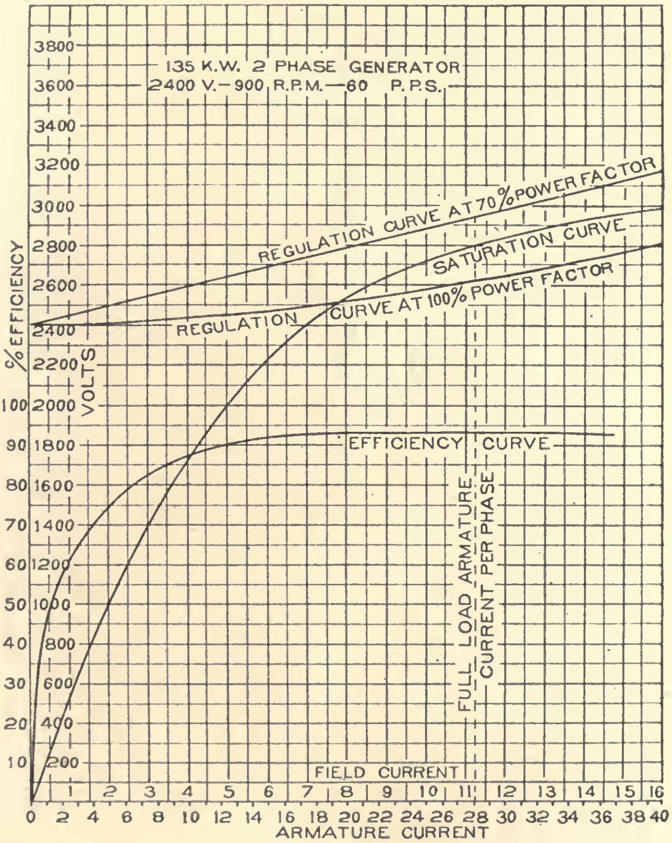


Fig. 159.

A series of observations is to be taken of the current in the armature, with the latter short-circuited through the ammeter. for different field currents, commencing at a very low value, and increasing the field current by successive steps until the armature current has reached a value of 100 per cent above its rated full-load value. The last few readings must be made quickly to prevent undue heating of the armature. The armature winding should be at approximately normal temperature when the test is made. The speed should be kept approximately at the rated speed of the machine. It is not as essential to keep the speed constantly at rated value as when observations are being made for the determination of the saturation curve. The observations to be recorded are the following:

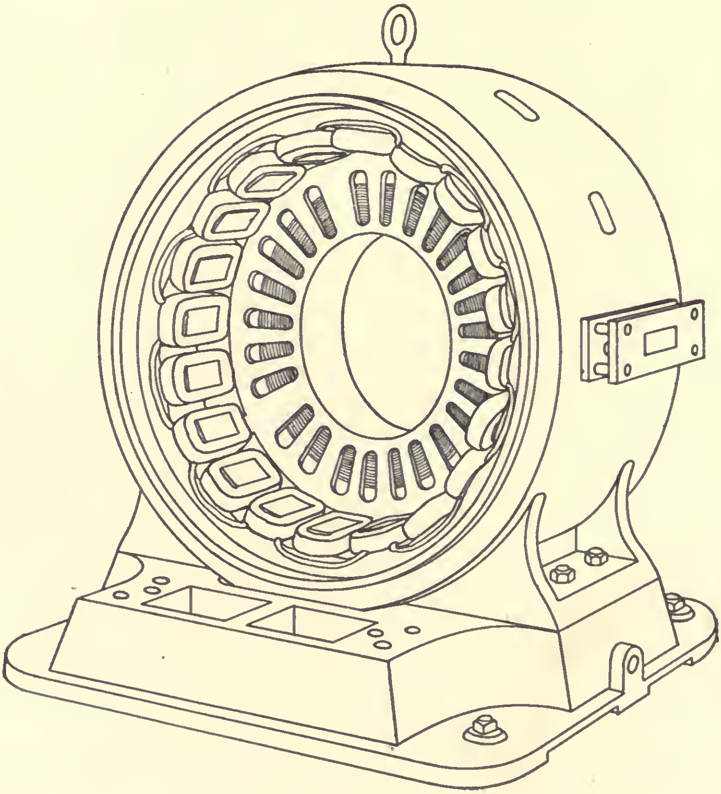


Fig. 160.

Amperes in the Armature.	Amperes in Field.	Volts at Field Terminals.	Speed.

Fig. 161 shows a curve giving the relation between electromotive force induced in the armature and the current in the armature when short-circuited through an ammeter. This figure relates to the same 2,000-kilowatt alternator whose saturation curve was given in Fig. 157. The electromotive forces plotted in this figure are not observed values, but the field excitations required to produce them are observed, and the electromotive forces corresponding to these field excitations are taken from the saturation curve, Fig. 157.

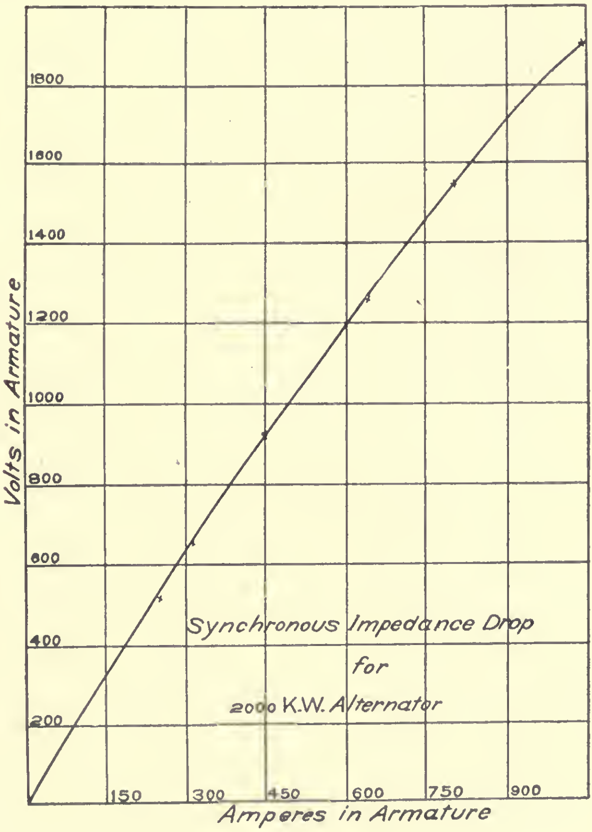


Fig. 161.

The total electromotive force induced in the armature for a given value of the field current may be read off from the no-load saturation curve of the machine, obtained as previously described. A curve may then be plotted with the electromotive force induced in the armature as ordinates, and the observed armature currents (on short circuit) as abscissas. This curve is sometimes called the **synchronous impedance curve**, although it does not explicitly show the values of the synchronous impedance of the armature. The synchronous impedance of the armature for a given value of armature current may, however, be derived from this curve by dividing the total electromotive force induced in the armature (ordinate) by the corresponding value of the short-circuited armature current (abscissa). For example, the synchronous impedance corresponding to 576 amperes (which is the full-load current per phase of the machine) is

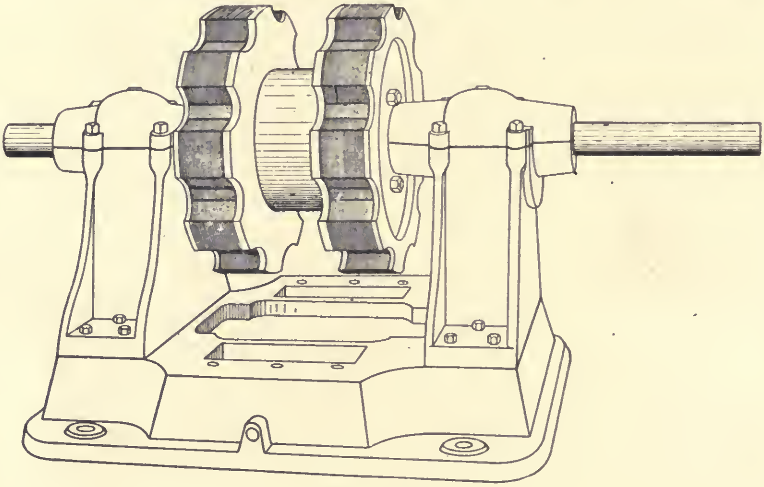


Fig. 162.

$$\frac{1{,}145 \text{ volts}}{576 \text{ amperes}} = 1.99 \text{ ohms.}$$

Synchronous impedance is used as a basis for the predetermination of the regulation of the machine, thereby avoiding the trouble and expense of an actual test of regulation under full load.

The synchronous impedance of an alternator armature is very nearly equal to the synchronous reactance of the armature, inasmuch as the armature resistance is usually small. Moreover the electromotive force required to overcome synchronous reactance is very nearly equal to the electromotive force required to overcome synchronous impedance.

63. Determination of Resistance of Armature. In the case of a three-phase armature, the resistance per phase cannot be measured directly between collector rings, since there are two phases in series between collector rings in a Y-connected armature; while in case of a Δ-connected armature, two phases in series are in parallel with the third phase between any two collector rings.

The resistance per phase can be measured either directly by Wheatstone bridge and galvanometer, or by the "fall of potential" method. In the case of a Y-connected armature the resistance per phase is one-half the resistance between terminals, provided that the resistance of all the phases are *alike.* In case the resistances of the phases are *unequal*, the resistance of any phase may be deduced as follows:

The resistance between terminals A and B, Fig. 163, is:

$$R_{AB} = a + b. \qquad (i)$$

The resistance between terminals B and C is:

$$R_{BC} = b + c. \qquad (ii)$$

The resistance between terminals C and A is:

$$R_{CA} = c + a. \qquad (iii)$$

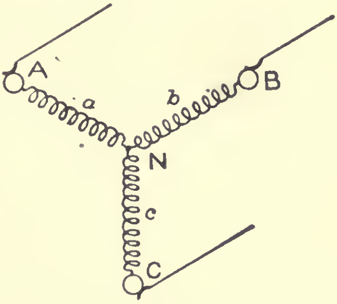


Fig. 163.

Then

$$a = R_{AB} - b \qquad (iv)$$
$$b = R_{BC} - c \qquad (v)$$
$$c = R_{CA} - a \qquad (vi)$$

Substituting (*vi*) in (*v*) we obtain:

$$b = R_{BC} - R_{CA} + a. \qquad (vii)$$

Substituting (*vii*) in (*iv*) we obtain:

$$a = R_{AB} - R_{BC} + R_{CA} - a,$$

from which $a = \dfrac{R_{AB} - R_{BC} + R_{CA}}{2}.$

Similarly we find: $b = \dfrac{R_{BC} - R_{CA} + R_{AB}}{2},$

and $c = \dfrac{R_{CA} - R_{AB} + R_{BC}}{2},$

If $R_{AB} = R_{BC} = R_{CA}$, then $a = b = c = \frac{R_{AB}}{2}$. For a Δ-connected armature with *equal* resistances per phase, the resistance per phase equals $\frac{3}{2}$ times the resistance between terminals. The general expression for the resistance of any phase can be deduced as in the above case for Y connection. In this case there are two circuits between A and B, one through the phase a, and the other through phases b and c in series, as shown in Fig. 164. Remembering that the joint resistance of two (or more) circuits in parallel is the reciprocal of the sum of the reciprocals of the resistances of the several branches, we have:

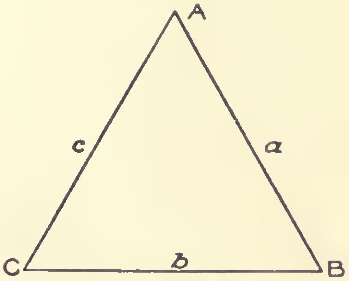


Fig. 164.

$$R_{AB} = \frac{1}{\frac{1}{a} + \frac{1}{b+c}},$$

$$R_{BC} = \frac{1}{\frac{1}{b} + \frac{1}{c+a}},$$

$$R_{CA} = \frac{1}{\frac{1}{c} + \frac{1}{a+b}}.$$

From these three equations the three unknown quantities a, b, and c, may be found by algebraic elimination as in the case of the Y connection.

64. Regulation.* The saturation and synchronous impedance curves of an alternator together with the resistance per phase of the armature, are all the data required for the computation of the regulation of an alternator. The direct determination of regulation by observation would be as follows:

> "The alternator would be run at normal rated speed, delivering rated full-load current with rated full-load electromotive force at its terminals. The main circuit would then be opened, thus reducing the current output to zero. The excitation would be left unchanged, and the rise of terminal electromotive force would be observed. Then,
>
> $$\text{Regulation in per cent.} = \frac{\text{rise of terminal electromotive force}}{\text{rated full-load terminal electromotive force}} \times 100.$$

This direct determination of regulation by observation is not feasible with large machines, on account of the large amount of power required. In all practical testing the regulation may be determined indirectly by calculation as follows:

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* See article 42.

When the alternator is operating at full load, the total electromotive force induced in the armature exceeds the terminal electromotive force by the amount lost in overcoming armature resistance, and by the amount lost in overcoming the synchronous reactance* of the armature.

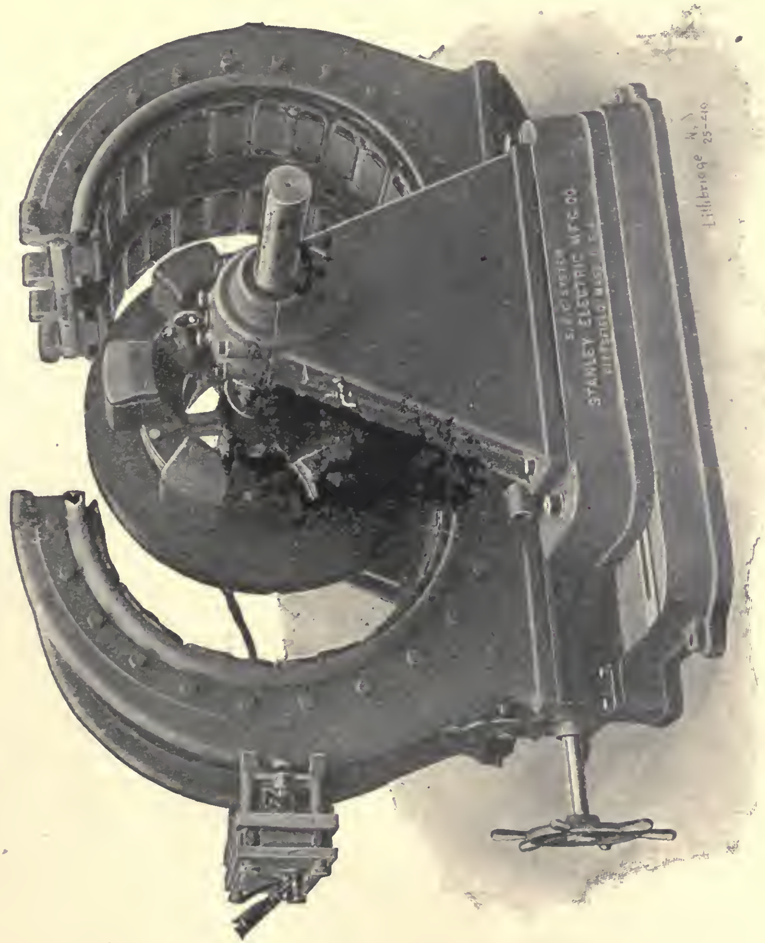

Fig. 165.

Let E be the total induced electromotive force in the armature of an alternator, E_t the terminal electromotive force at full load, RI the electromotive force lost in overcoming armature resistance, and XI the electromotive force lost in overcoming the synchronous reactance of the armature. The electromotive force required to produce the current I through the short-circuited armature may be found from the "synchronous impedance curve" (Fig. 161) by taking the ordinate corresponding to the value of I (abscissa). The electromotive force so found is nearly equal to XI on account of the relative smallness of armature resistance, and

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* See article 41.

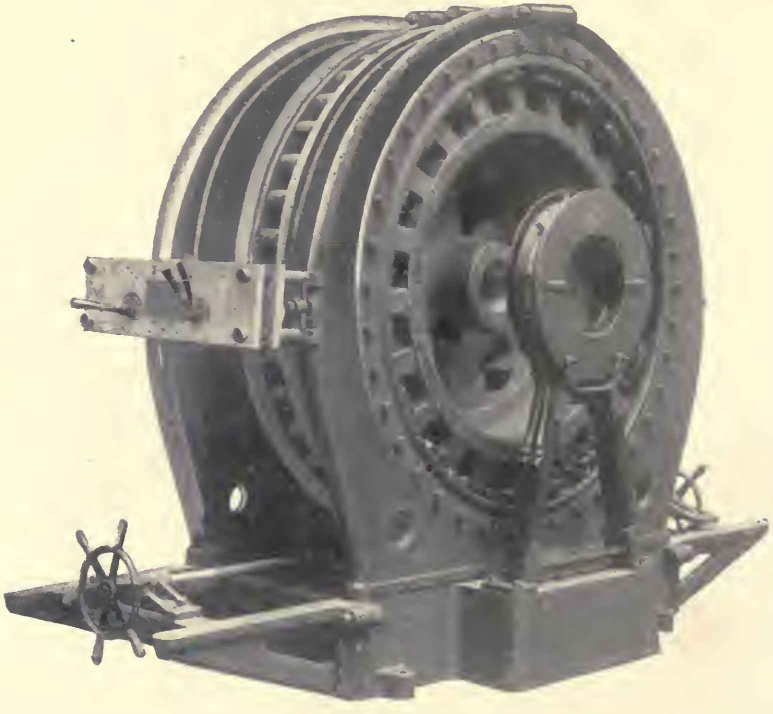


Fig. 166.

especially on account of the fact that RI and XI are at right angles to each other. In other words, the synchronous impedance is in most practical cases approximately equal to the synchronous reactance.

Therefore the electromotive force found from the synchronous impedance curve may be taken as the value of XI.

Knowing the electromotive force lost in overcoming the synchronous reactance, we can find from the saturation curve the amount of field excitation (abscissa) required to produce this electromotive force (ordinate).

This field excitation is represented by the line OB, Fig. 167. Take from the saturation curve the field excitation corresponding to rated terminal voltage at full load, and represent it by the line OA, Fig. 167. Next find the geometric sum, OC, of OA and OB. This OC represents the field excitation required at full load to produce rated terminal electromotive force. The electromotive force produced by this excitation at zero load may be taken from the saturation curve. The difference between the rated electromotive force of the alternator and the electromotive force so found, is the rise of electromotive force from full load to zero load; and this rise divided by the rated electromotive force and multiplied by 100 gives the regulation of the alternator in per cent.

The diagram, Fig. 167, applies to a non-inductive receiving circuit. When the receiving circuit is inductive, the angle BOA, Fig. 167, should be $90 - \theta$, in which θ is the angle of lag of the current behind the electromotive force at the terminals of the alternator. The cosine of this angle is the power factor of the receiving circuit.

The above rule for calculating regulation is much used in practice, and is recommended by the Committee on Standardization of the American Institute of Electrical Engineers; but the rule is open to criticism.

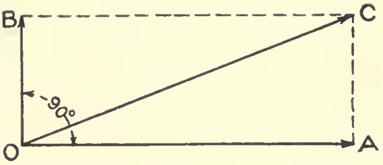


Fig. 167.

Example. The synchronous impedance and saturation curves shown in Figs. 161 and 157 are taken from tests upon a Δ-connected three-phase 2,000-K.W. 16-pole 2,000-volt revolving-field alternator having a speed of 300 r.p.m. The full-load armature current is 576 amperes per phase. The armature resistance per phase is 0.009239 ohms. Hence the RI drop in the armature = $(576 \times 0.009239) = 5.3$ volts. $E_t = 2{,}000$; $E_t + RI = 2{,}000 + 5.3 = 2005.3$ volts.

From the saturation curve, Fig. 157, we find that it requires 83.5 amperes in the field winding to generate this 2,005.3 volts at no load. This represents the component OA in Fig. 167. From the synchronous impedance curve, Fig. 161, we find that 1,137 volts in the armature are required to force the full-load current of 576 amperes per phase through the armature. From the saturation curve we find that 1,137 volts correspond to 43 amperes in the field winding. The component OB in Fig. 167 is therefore 43 amperes. The full-load field current

$$OC = \sqrt{OA^2 + OB^2} = \sqrt{43^2 + 83.5^2} = 93.8 \text{ amperes.}$$

This field current would produce at zero load an electromotive force of 2,169 volts, as shown by the saturation curve. Therefore, according to the definition of regulation, as previously explained, we have:

$$\text{Regulation} = \frac{2{,}169 - 2{,}000}{2{,}000} \times 100 = \frac{169}{2{,}000} \times 100 = 8.45 \text{ per cent.}$$

If the regulation had been desired at a power factor other than unity (for instance, at 85 per cent power factor), the field current OB, Fig. 167, would not be taken at right angles to OA to find the resultant field current OC at full load, but the angle BOA would be decreased by the angle whose cosine is 0.85, or by 31.75°. The resultant field current OC is represented as before, by the diagonal of the parallelogram; but it is no longer equal to the square root of the sum of the squares of OA and OB. The calculation of the regulation in case of 85 per cent power factor is as follows:

The angle BOA, Fig. 167, now is 58.25°, and

$OC^2 = OA^2 + OB^2 + 2\,\overline{OA}\,\overline{OB}\,\text{Cos. } 58.25°$,

whence OC = 112 amperes.

By referring to the saturation curve we find that a full-load field current of 112 amperes would produce 2,375 volts at no load. Hence the regulation at 85 per cent power factor is:

$$\frac{2{,}375 - 2{,}000}{2{,}000} \times 100 = \frac{375}{2{,}000} \times 100 = 18.75 \text{ per cent.}$$

This example illustrates the general fact explained in article 42, that the electromotive force at the terminals of an alternator suffers a greater decrease in value on an inductive load (power factor less than unity) than on a non-inductive load (power factor unity) for the same current output.

Fig. 159 shows the regulation curves of a two-phase 135-kilowatt 2,400-volt 60-cycle S. K. C. inductor alternator. The lower regulation curve shows the regulation of the alternator at 100 per cent power factor (that is, on non-inductive load); and the upper regulation curve shows the regulation of the alternator at 70 per cent power factor. The abscissa of a given point on one of these regulation curves represents a given current output per phase of the machine; and the ordinate of the point represents the voltage obtained at the armature terminals when this armature current is reduced to zero, the field current being kept constant at that value which gives the rated voltage of 2,400 volts with the given current output per phase.

For example, with full-load current output, namely 28.1 amperes per phase and 100 per cent power factor, the voltage rises from 2,400 to 2,625 (the ordinate of the regulation curve for 100 per cent power factor corresponding to the abscissa representing 28.1 amperes of armature current) when the load is thrown off (armature current reduced to zero) the field current remaining unchanged. From these data the full load regulation of the machine on 100 per cent power factor is found to be:

$$\frac{225}{2{,}400} \times 100 = 9.4 \text{ per cent.}$$

With half-load current output, namely 14.05 amperes per phase, and 70 per cent power factor, the voltage rises from 2,400 to 2,650 when the load is thrown off, the field current remaining unchanged. From these data the half-load regulation of the machine at 70 per cent power factor is found to be:

$$\frac{250}{2{,}400} \times 100 = 10.4 \text{ per cent.}$$

These curves show that the regulation of the machine is higher on inductive loads than on non-inductive loads, as was explained in article 42.

The following are the recommendations of the American Institute of Electrical Engineers concerning the regulation of alternators and their prime movers.

"(50) The term 'regulation' should have the same meaning as the term 'inherent regulation', at present frequently used.

"(51) The regulation of apparatus intended for the generation of constant potential, constant current, constant speed, etc., is to be measured by the maximum variation of potential, current, speed, etc., occurring within the range from full load to no load, under such constant conditions of operation as give the required full-load values, the condition of full load being considered in all cases as the normal condition of operation.

"(53) The regulation is given in percentage of the full-load value of potential, current, speed, etc.; and the apparatus should be steadily operated during the test under the same conditions as at full load.

"(54) The regulation of generators is to be determined at constant speed; of alternating apparatus, at constant impressed frequency.

"(55) The regulation of a generator-unit, consisting of a generator united with a prime mover, should be determined at constant conditions of the prime mover, *i. e.*, constant steam pressure, head, etc.. It would include the inherent speed variations of the prime mover. For this reason the regulation of a generator-unit is to be distinguished from the regulation either of the prime mover, or of the generator contained in it, when taken separately.

"(56) In apparatus generating, transforming, or transmitting alternating currents, regulation should be understood to refer to non-inductive load, *i.e.*, to a load in which the current is in phase with the e.m.f. at the output side of the apparatus, except where expressly specified otherwise.

"(57) In alternating apparatus receiving electric power, regulation should refer to a sine wave of e.m.f., except where expressly specified otherwise.

"(58) In commutating machines, rectifying machines, and synchronous machines, as direct-current generators and motors, alternating-current and polyphase generators, the regulation is to be determined under the following conditions:

a. At constant excitation in separately excited fields;

b. With constant resistance in shunt field circuits; and

c. With constant resistance shunting series fields; *i. e.*, the field adjustment should remain constant, and should be so chosen as to give the required full-load voltage at full-load current.

"(59) In constant-potential machines, the regulation is the ratio of the maximum difference of terminal voltage from the rated full-load value (occurring within the range from full load to open circuit) to the full-load terminal voltage.

"(60) In constant-current apparatus, the regulation is the ratio of the maximum difference of current from the rated full-load value (occurring within the range from full load to short circuit, or minimum limit of operation) to the full-load current at constant speed, or, in transformers, etc., at constant impressed voltage and frequency.

"(68) In steam engines, the regulation is the ratio of the maximum variation of speed in passing from full load to no load (at constant steam pressure at the throttle) to the full-load speed.

"(69) In a turbine or other water-motor, the regulation is the ratio of the maximum variation of speed from full load to no load (at constant head of water, *i.e.*, at constant difference of level between tail race and head race) to the full-load speed".

65. Heat Test. The heat test is made by running the generator under full-load conditions until a constant temperature has been reached. When this condition has been attained the machine is shut down, and the temperature of the various parts is taken by thermometers placed against the heated surfaces. The resistances of the armature and field windings are also measured while hot. By comparing these "hot" resistances with the same resistances previously measured at room temperature, the temperature rise of the armature and field coils can be computed. The temperatures usually recorded are as follows:

Armature coils.
" laminations.
" ventilating ducts.
Frame.
Bearings.
Field coils.
Pole tip (leading).
" " (trailing).
Field yoke.
Room.

Small generators are usually run at full load, delivering their output to water rheostats. During the heat run, thermometers, placed on different parts of the machine, are read regularly. If the generator is of the revolving-armature type, a thermometer is placed against the field winding, and another thermometer is so placed that the hot air issuing from the ventilating ducts will come in contact with it. If the generator be of the revolving-field type, thermometers are placed against the armature coil, on the armature laminations, and in the ventilating ducts. When these thermometers do not show an increasing temperature, and the resistance of the field, as determined from the field ammeter and voltmeter, has become constant, the machine is considered as having attained its ultimate temperature, and is shut down for the application of thermometers. These thermometers should be ready for immediate application, inasmuch as the machine cools off rapidly. The time taken by a machine to reach constant temperature varies from 3 to 4 hours in the case of a small machine, and from 12 to 24 hours for very large ones.

The following maximum values of temperature elevation have been recommended by the Standardization Committee of the American Institute of Electrical Engineers:

Field and armature, 50°C by resistance.
Collector rings and brushes, 55°C by thermometer.
Bearings and other parts of machine, 40°C by thermometer.

The rise of temperature should be referred to the standard conditions of a room-temperature of 25°C, a barometric pressure of 760 mm., and normal conditions of ventilation; that is, the apparatus under test should neither be exposed to draft, nor enclosed, except where expressly specified.

If the room-temperature during the test differs from 25°C, the observed rise of temperature should be corrected by $\frac{1}{2}$ per cent for each degree C. Thus, with a room temperature of 35°C, the observed rise of temperature has to be decreased by 5 per cent; and with a room-temperature of 15°C, the observed rise of temperature has to be increased by 5 per cent. The thermometer indicating the room-temperature should be screened from thermal radiation emitted by heated bodies or from drafts of air. When it is impracticable to secure normal conditions of ventilation on account of an adjacent engine, or other sources of heat, the thermometer for measuring the air-temperature should be placed so as to fairly indicate the temperature which the machine would have if it were idle, in order that the rise of temperature determined shall be that caused by the operation of the machine.

The temperature should be measured after a run of sufficient duration to reach practical constancy. This is usually from 6 to 18 hours, according to the size and construction of the apparatus. It is permissible, however, to shorten the time of the test by running a lesser time on an overload in current and voltage, then reducing the load to normal, and maintaining it thus until the temperature has become constant.

In making a heat test of a large alternator it is customary to imitate full-load conditions, electrically and magnetically, so as to produce all the heating effects that would occur under actual full load, but without taking any actual electrical power from the alternator. To be able to do this is of great advantage from two standpoints: first, that of convenience; and, second, that of economy. To accomplish this desirable result the generator is usually run on short circuit with a number of the field spools connected in opposition to (or "bucked" against) the remainder; or, in other words, with the effective number of poles reduced.

To determine the proper number of field magnet spools to be connected in opposition, we proceed in the following manner:

It was previously explained that from the saturation and synchronous impedance curves of a generator, we can determine the field current required to produce rated voltage at full load. In the case of the 2,000-K.W. generator, of which the curves are given in Figs. 157 and 161, the normal full-load field current was found to be 93.8 amperes. This field current would, if the armature were short-circuited, produce, according to Fig. 161, an armature current of more than 1,050 amperes, which is greatly in excess of rated full-load current. If the field current were reduced to 43 amperes, the armature current would be normal; but the field current, and therefore the magnetic density in the field magnet and armature core, and the consequent iron losses in the armature, would be very much below normal.

In this example we may reduce the excessive current in the short-circuited armature to its normal full-load value by reducing the effective number of field poles in the ratio of 93.8 to 43 instead of by reducing the field current in this ratio. The alternator has 16 field poles, and to reduce their number in the ratio of 93.8 to 43, would leave $\frac{16 \times 43}{93.8} = 7.34$ poles; but inasmuch as there must be an integral and even number of field poles, the closest approximation to the desired number is 8 effective poles. If, therefore, we reverse the connections of any four (adjacent) field coils, the four poles produced by these reversed field coils will be reversed in polarity; and the electromotive forces induced in the armature conductors under these reversed poles will be reversed, and will balance the electromotive forces induced in the armature conductors under four of the unreversed field poles, so that the electromotive forces induced in the armature conductors under the remaining eight poles, only, will be effective in producing current in the armature. That is, only eight field poles will be effective.

If, under these conditions, we short-circuit the armature of the alternator, it will take approximately the full-load field current of 93.8 amperes to produce full-load current in the armature, and the heat test can then be made under full-load conditions—namely, full-load armature current, full-load field current, and full-load iron losses, while the machine is running on short circuit, and therefore delivering no power. Only the power represented by the losses occurring in the machine, need be supplied to drive it. This is the method used in practice. If the normal field current does not give normal armature current, after the spools are connected in opposition as described, the effect of a slight excess of armature current may be approximately balanced by a slight deficiency of field current, or *vice versa.*

66. Core Loss and Friction Test. For this test the generator is run at normal speed on open circuit. The power required to drive it, its field current being zero, is measured. The power so measured is the power lost in friction and windage. Then the field current is increased, step by step, until the terminal electromotive force has increased to from 25 to 50 per cent above its normal rated full-load value ; the terminal voltage is observed at each step, the armature being on open circuit (main switch open). The power required to drive the machine at each of these observed voltages is determined. This power is used to supply friction and windage loss and iron (or core) loss at the observed voltage.

The difference, therefore, between the power required to drive the machine at a given voltage on open circuit, and the amount of power required to drive the machine without field excitation (that is, to supply the friction and windage loss) represents the iron loss (or core loss) at the given voltage. Fig. 168 shows the no-load core loss curve for the 2,000-K.W. alternator of which the saturation curve and the synchronous impedance curve are given in Figs. 157 and 161.

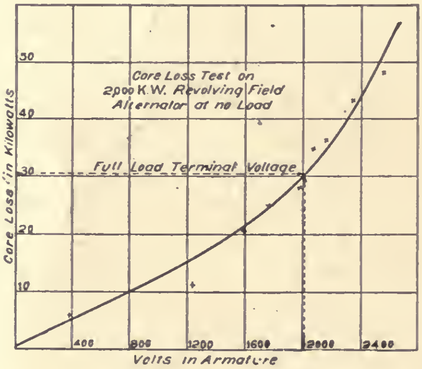
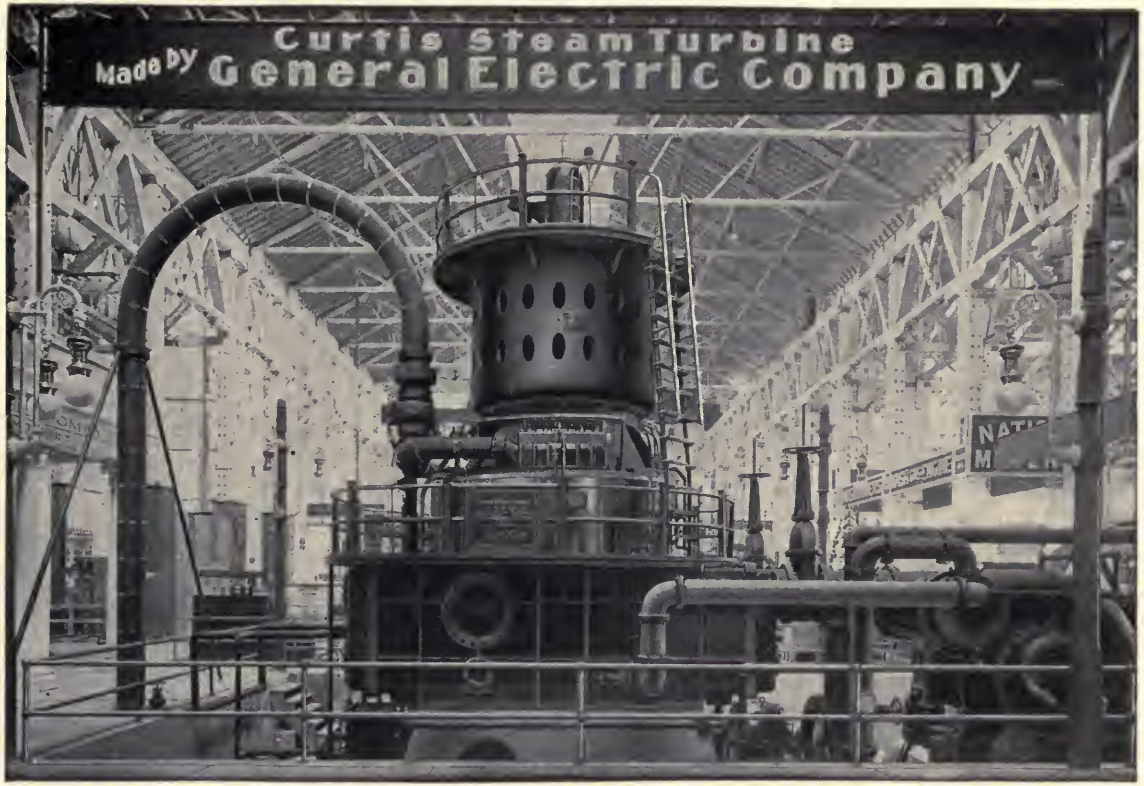


Fig. 168.

The most convenient way to measure the power delivered to the alternator is to drive it by a motor and measure the electrical input to the motor. If we determine the losses occurring in the motor the difference between the input to the motor and these losses is the power delivered to the alternator. Fig. 169 shows a diagram of complete connections for the carrying out of the core loss test. A is the alternator under test. Its voltage is measured by the voltmeter V_1 connected to the secondary of the potential transformer T. Its field current, supplied by the exciter E, is measured by the ammeter A_1 and regulated by the resistance RE



CURTIS TURBINE DRIVING ALTERNATING-CURRENT GENERATOR.

General Electric Company.

in the field of the exciter. The power is supplied to the motor M by the direct-current generator G. This power is measured by the ammeter A_2 and the voltmeter V_2. The motor M is separately excited, its field current being measured by the ammeter A_3. This field current is kept constant by adjusting the rheostat R_F.

As the field current and voltage of the generator under test are increased, the load on the driving motor M is increased also, since the hysteresis and eddy current loss in the generator, which must be supplied by the motor, are increased. As the load on the motor increases, it will slow down if its field current, and the voltage between its brushes, remain constant. However, the alternator to be tested must be run at constant speed, and its speed is controlled by varying the voltage at the motor terminals by means of the field rheostat R_G of the direct-current generator G. In the figure the field rheostat R_G of the generator G, is shown beside the alternator A. It is placed at this point so that the man who is observing the speed of the alternator can keep the speed under control.

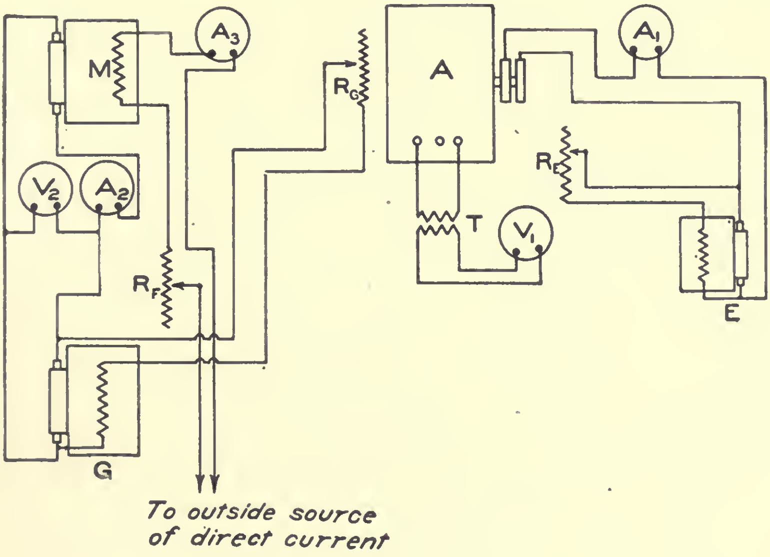


Fig. 169.

The input to the motor armature in watts is equal to the product of the readings V_2 and A_2. Part of this input is consumed in supplying the various losses in the motor armature, including friction and windage; and the remainder is converted into useful mechanical power, and is transmitted by the belt (not shown in Fig. 169) to the pulley of the alternator A, which is being tested. In other words the watts input to A is equal to the input to the armature of M minus the various losses in the armature of M. The losses in the armature of M consist of hysteresis, eddy current, friction, windage and I^2R losses. Since the alternator is to be run at constant speed, the motor will also run at constant speed if there is no belt slip, which should be the case; and since the motor runs at constant speed and at a constant field excitation, all the losses in the motor armature will be constant in value, whatever its load, except the I^2R loss. This I^2R loss varies because the current I varies for different loads on the motor. If the speed of the motor were regulated by varying its field current, instead of varying the voltage applied at its terminals, the above-mentioned losses in the motor armature would not remain constant; hence the latter method is adopted.

If the motor be run free, *i.e.*, with belt off, the output of the motor will be zero, and therefore the input must be used up entirely in overcoming the losses. Let E be the voltage at motor brushes, and I the current in the motor armature when it is running free (or unloaded), then $EI =$ stray power $+ RI^2$, where "stray power" equals the sum of all the constant losses in the motor armature (*i.e.*, hysteresis, eddy current, friction, and windage losses). Hence, stray power $= EI - RI^2$.

The mechanical or useful output of the motor at a given load, the voltage applied to its brushes being E_1, and its armature current being I_1, is:

$$\text{Output} = E_1I_1 - R_1I_1^2 - \text{stray power}.$$

That is, the mechanical output is equal to the total electrical input minus the total losses.

The stray power can be determined once for all by running the motor free (or at no load) at the speed and with the field current used in the test when E and I were observed. Thus, we may determine the power required to drive A (the machine to be tested) with zero field excitation of A, in which case we obtain its friction and windage losses; and we may determine the power required to drive A at any given field excitation and voltage, in which case we obtain the sum of the friction, windage, and core (or iron) losses.

In carrying out the test the following procedure is found most convenient:

First, the motor is made to drive the alternator with zero field current in the latter; and a number of observations are taken, as indicated in the tabular arrangement below. This is to determine the friction and windage loss of the alternator. Then the alternator is excited to produce a series of values of terminal voltage, for each of which a similar set of observations is taken; and so on, until the voltage of the alternator has been increased to about 25 per cent above normal rated voltage. The motor is now shut down and its belt thrown off, and it is run unloaded in order to determine its own stray-power losses. Finally the motor is shut down, and the resistance of its armature is measured.

For each set of readings the following observations should be recorded:

Motor.				Alternator.		
Volts at Brushes.	Amperes in Armature.	Amperes in Field.	Speed.	Volts at Terminals.	Amperes in Field.	Speed

The amperes in the field of the motor, and the speed of the motor and generator are recorded merely to show whether they have been kept constant during the test. For the best results the motor should have a rated capacity of from 15 to 20 per cent of the rated capacity of the machine to be tested.

Example. In a core loss test of the 2,000-kilowatt alternator above referred to, the following observations were taken: With zero field excitation of the alternator, the voltage applied to the motor armature and the current in the motor armature were 510 volts and 48 amperes respectively. When the alternator was excited to give 2,070 volts between its terminals, the volts applied to, and the current in, the motor armature were 511 volts and 117 amperes respectively. With the motor running unloaded the voltage applied to, and the current in, the motor armature were 509 volts and 11.5 amperes respectively. The resistance of the armature of the motor was 0.056 ohm.

(*a*) The stray-power loss of the driving motor is calculated from the readings taken above when the motor was running unloaded, as follows:

Motor input was 509 volts × 11.5 amperes = 5,853 watts. But by definition, stray power = $EI - RI^2$. Hence, stray power = 5,853 - 0.056 × $(11.5)^2$ = 5,846 watts.

(*b*) The friction and windage loss of the alternator is then calculated as follows:

Power supplied to motor when driving alternator at full speed with zero field excitation was 510 volts × 48 amperes = 24,480 watts; and the useful output of the motor or the power used to drive the alternator was the power input to the motor minus stray-power loss and minus I^2R loss in its armature. Therefore,

Friction and windage loss of alternator = 24,480 - 5,846 - $(48)^2$ × 0.056 = 18,505 watts.

(*c*) The core (or iron) loss of the alternator is then calculated as follows:

Power supplied to motor when driving the alternator at full speed, field excited to give 2,070 volts between alternator terminals, was 511 volts × 117 amperes = 59,787 watts. The useful output of the motor in this case was 59,787 watts - 5,846 watts - $(117)^2$ × 0.056 = 53,175 watts; and this is equal to the sum of friction and windage loss and iron loss. Therefore,

Core loss of the alternator = 53,175 - 18,505 = 34,670 watts.

The core loss of the alternator was calculated for *each* value of the field excitation of the alternator in a manner similar to the above. These various core losses are plotted as ordinates of the curve in Fig. 168, the abscissas being the electromotive forces between alternator terminals corresponding to the various field excitations. This curve shows that at the rated full-load voltage, namely, 2,000 volts, the core loss of the alternator is 30.5 kilowatts or 1.025 per cent of the rated full-load output of the alternator.

67. Calculation of Efficiency. Since the efficiency of an alternator is the ratio of the output to the output plus the losses, as explained in article 59, we may now calculate the efficiency of the alternator, having made all necessary tests. In the case of the 2,000-K.W. alternator referred to above, for which the curves have been given, the following losses occur:

(*a*) *Friction and Windage Loss.* This loss was found to be 18,505 watts.

(*b*) *I^2R Loss in Armature at Full Load.* The resistance of each phase of the armature winding of the given alternator was measured and found to be 0.00924 ohm, and the full-load rated current is 576 amperes per phase. Therefore the I^2R loss per phase is

$$(576)^2 \times 0.00924 = 3,065 \text{ watts.}$$

Hence the total I^2R loss for all three phases is

$$3 \times 3,065 \text{ watts} = 9,195 \text{ watts.}$$

(*c*) *I^2R Loss in the Field.* The resistance of the field winding of the given alternator is 0.966 ohm, and the full-load field current is 93.8 amperes. Hence I^2R loss in the field is 8,500 watts.

(*d*) *Core Loss.* The core loss on open circuit at full-load excitation was found to be 30,500 watts. This is somewhat less than the core loss would be with full-load excitation and with full-load armature current.

Therefore the sum of all the losses is:

Friction and windage	18,505
I^2R loss in armature	9,195
I^2R loss in the field	8,500
Core loss	30,500
	66,700 watts.

The rated full-load output being 2,000 kilowatts, we have:

$$\text{Efficiency at full load} = \frac{2,000,000}{2,000,000 + 66,700} = 0.968$$
$$= 96.8 \text{ per cent.}$$

If the efficiency at any fractional part of full load is desired, it may be calculated as follows:

$$\frac{\frac{1}{2}\text{ rated full-load output}}{\frac{1}{2}\text{ rated full-load output} + \text{losses at half load}}$$

(*a*) Friction and windage loss is approximately the same at half load as at full load.

(*b*) I^2R loss in the armature is one fourth as great as at full load since the armature current is half as great.

(*c*) I^2R loss in the field is slightly less at half load than at full load, inasmuch as field current is slightly less.

(*d*) Core loss at half load is slightly less than core loss at full load.

Fig. 159 shows the efficiency curve of a two-phase 135-kilowatt 2,400-volt 60-cycle S.K.C. inductor alternator. The ordinates of this efficiency curve represent the efficiencies of this alternator corresponding to different current outputs per phase, the latter being plotted as abscissas. The efficiencies shown by this curve apply to the machine when it delivers power to non-inductive receiving circuits (100 per cent power factor) When the power factor is less than 100 per cent, the efficiencies are less than the efficiencies shown by the curve.

At full-load current output of 28.1 amperes per phase and 100 per cent power factor, the efficiency as represented by the ordinate of the curve is 93 per cent. At half-load current output of 14.05 amperes per phase, the efficiency is $90\frac{1}{2}$ per cent. At full load the several losses in this machine are as follows:

(*a*) Friction and windage loss (obtained by experiment), 2,000 watts.

(*b*) I^2R loss in the armature (calculated from hot resistance of armature 1.46 ohm. per phase, and full-load armature current 28.1 amperes per phase) is:

$$2 \times (28.1)^2 \times 1.46 = 2{,}305 \text{ watts.}$$

(*c*) I^2R loss in the field (calculated from hot resistance of field coil 9.35 ohms, and full-load field current 8.8 amperes) is:

$$9.35 \times (8.8)^2 = 724 \text{ watts.}$$

(*d*) Core loss (determined by experiment using the method described in article 66), 5,000 watts.

The total loss is therefore:

Friction and windage loss,	2,000 watts
I^2R loss in armature,	2,305 "
I^2R loss in field,	724 "
Core loss,	5,000 "
Total loss,	10,029 watts.

Therefore the efficiency at full load is

$$\frac{135{,}000}{135{,}000 + 10{,}029} = 93 \text{ per cent.}$$

68. Determination of Electromotive Force Waves. The electromotive force wave of an alternator is determined by actually measuring the successive instantaneous values of the electromotive force. For this purpose an instantaneous-contact device, called a **contact-maker** is used to connect the alternator terminals repeatedly to the terminals of a voltmeter, successive contacts occurring at corresponding instants in succeeding cycles. The voltmeter is steady because of the frequency of the contacts and it indicates the value of the electromotive force at a particular part of the cycle. The contact device is then adjusted to make successive contacts at a later instant in each cycle, and the voltmeter is again read; and so on. The voltmeter must be one which takes little or no current, such as an electrostatic voltmeter; and a condenser should be connected to the voltmeter terminals (in parallel with the voltmeter) in order that enough current may flow into the condenser at each contact to keep the voltage between the voltmeter terminals up to nearly its full value during the intervals between contacts. If the condenser is not used, the voltmeter readings are likely to be too low.

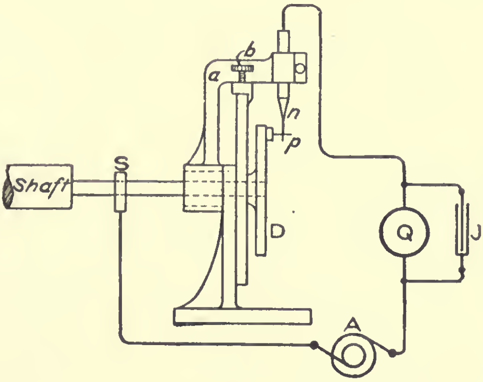


Fig. 170.

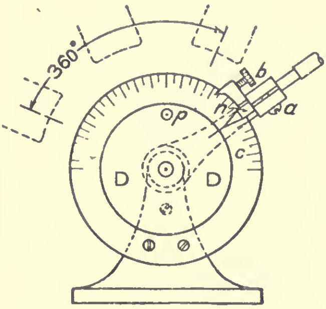


Fig. 171.

A side view of a water-jet contact-maker is shown in Fig. 170, and an end view is shown in Fig. 171. The latter figure also shows in dotted outline three adjacent poles of the field magnet of the alternator to which the contact-maker is attached. A disc DD, is fixed to a spindle which is rigidly coupled to, but insulated from, the shaft of the alternator A. This disc carries a pin *p*, which makes momentary contact, once per revolution, with a fine jet of salt water issuing from a nozzle *n*. This nozzle is carried on an arm *a*, which is loose on the spindle and can be placed in any desired position and clamped by means of the screw *b*, its position being read off the divided circle *cc*. The collecting rings and brushes of the alternator are shown diagrammatically at A. One terminal of an electrostatic voltmeter Q is connected directly to one brush of the alternator A; while the other terminal of the voltmeter is connected through the jet, pin, and sliding contact *s*, to the other brush of the alternator, as shown in Fig. 170. The voltmeter then indicates the value of the electromotive force of the alternator at the instant of contact of jet and pin. By shifting the jet, step by step, around the circle, values of the electromotive force at successive instants during a cycle are indicated by the reading of the voltmeter The electromotive force passes through a complete cycle of values while the jet is shifted $\frac{2}{p}$ of a revolution, p being the number of poles of the alternator. In order that the electromotive force acting upon the electrostatic voltmeter may not fall off appreciably in the intervals between successive contacts of pin and jet, a condenser J is connected as shown in Fig. 170.

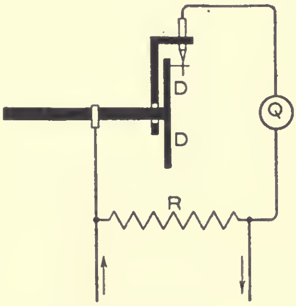


Fig. 172.

In the determination of an alternating-current curve, the current is sent through a non-inductive resistance, as R, Fig 172; and the curve of the electromotive force between the terminals of this resistance is determined as before, the disc DD being fixed to the armature shaft of the alternator that is furnishing the current. The current at each instant is equal to the electromotive force divided by R.

A flat metal spring or brush is sometimes used instead of the liquid jet in Fig. 170. In this case the pin p is replaced by a strip of metal set in the edge of a circular disc of hard rubber, and the spring rubs continuously upon the edge of this disc, touching the metal strip momentarily once per revolution of the disc

Fig. 173 is a curve showing the successive instantaneous values of the electromotive force of a 35-kilowatt 125-cycle single-phase alternator, as determined by a contact-maker. The highest point (1,400 volts) is given where the conductors are passing through the most intense portion of the field. The flat top of the curve shows that the magnetic intensity was nearly uniform over a large portion of the pole face. The curve crosses the axis (electromotive force equals zero) in the neutral plane between two poles. The curve shows one complete cycle, that is, it shows the instantaneous values of the electromotive force in one conductor while passing one pair of poles.

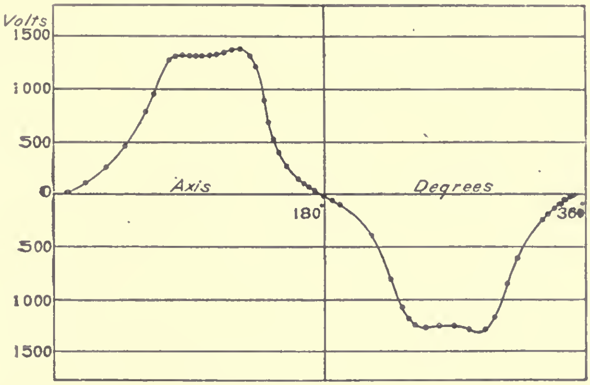


Fig. 173.

The effective value of the electromotive force of the alternator, as indicated by a voltmeter connected to the alternator terminals during the observations with the contact-maker, was found to be 1,000 volts; and this is the square root of the average value of the squares of the successive values as observed by means of the contact-maker.

SYNCHRONOUS MOTORS.

69. Synchronous Motors and Induction Motors. Motors designed to be operated with alternating currents may be divided into two classes:

1. Synchronous Motors.
2. Induction Motors.

Both kinds are in common use; and, although there are a few other motors which do not come under the above classification, yet by far the larger part of all the motors run with alternating currents belong to one or the other of these classes. The induction motor having properties which adapt it to a much wider field of application than is possible with the synchronous motor, is much the more commonly used. The induction motor is treated subsequently.

70. The Synchronous Motor. When a given armature conductor of an alternating-current generator is under a north pole of the field magnet, the current in the conductor is in a direction such that the force which the field exerts on the wire opposes the motion of the armature. When the given conductor has moved sufficiently to be under a south pole of the field magnet, the current will have reversed in direction, and the force which the field exerts on the wire will still oppose the motion of the armature. The work done in driving the armature against these opposing electromagnetic forces, is the work that goes to maintain the alternating current delivered by the alternator.

Consider an alternator driven by a small engine or auxiliary motor. Let an alternating current from an outside source be forced through the revolving armature of the alternator, the field magnet of which is supplied with a direct current from an exciter. Then the motion of the revolving armature will be helped by the alternating current if the following conditions are satisfied:

(*a*) If the speed of the armature is such that a given armature conductor moves from the middle of a north pole to the middle of a south pole during the time of one alternation (half a cycle) of the supplied alternating current.

(*b*) If the direction of the supplied alternating current, when the given conductor is under a north pole, is such that the force exerted upon the conductor by the field helps the motion of the armature.

This is evident when we consider that the current reverses every time the given conductor passes from one field pole to the next, and that this reversed current will be acted upon by the reversed polarity of the next pole with a force always in the direction of the motion.

When the alternator speed has been carefully adjusted so that the conditions *a* and *b* are satisfied, the driving engine or auxiliary motor may be disconnected; the armature of the alternator will continue to revolve at constant speed (the frequency of the supplied alternating current being constant), and the revolving armature may deliver power by belt to drive machinery. An alternator used in this way is called a **synchronous motor.**

Any alternator may be used as a synchronous motor without alteration of any kind. Electrically and mechanically, the synchronous motor is the same as the alternating-current generator. In fact the same machine is often used indifferently as motor or generator according to circumstances. Composite field winding is never provided on an alternator which is to be used as a synchronous motor.

Synchronous motors may be designed to operate either on single-phase or polyphase systems, and are called synchronous because they always run in synchronism with (*i.e.*, at the same frequency as) the alternator supplying the current to them. The speed of the motor cannot change unless the speed of the generator changes; but it is not necessarily the same speed as that of the generator. The speed of the motor will be the same as the speed of the generator only when the motor happens to have the same number of poles as the generator. The speed at which a synchronous motor will run when connected to an alternator supplying current at a frequency f, is

$$s = \frac{2 \times f \times 60}{p},$$

where s = speed of the motor in revolutions per minute;
f = frequency of the alternating-current supply;
p = number of poles on the motor field
For example, if a 10-pole motor were run from a 60-cycle alternator, the speed of the motor would be

$$\frac{2 \times 60 \times 60}{10} = 720 \text{ r.p.m.}$$

Moreover, it follows that if the motor had the same number of poles as the alternator, the speed of the motor would be just the same as the speed of the alternator, and any variation in the speed of the latter would cause a corresponding change in the speed of the motor; or if the motor had half as many poles as the generator its speed would be double that of the latter, and any change in the speed of the generator would cause a proportional change in that of the motor; in other words, the cyclic speeds must be the same.

The synchronous motor, especially in units of large output, possesses a number of features which make its use at times preferable to that of the induction motor. Its advantages may be briefly summed up as follows:

(*a*) Unvarying speed at all loads.

(*b*) Power factor, variable at will by change of the exciting current, can be made approximately unity at any load.

(*c*) The current in the armature can be made to lead the electromotive force by over-exciting the field magnets, thus producing the same effect as a large condenser. The leading current in the armature can be used to neutralize the unfavorable effects of inductance (which causes lagging currents) in other parts of the system.

(*d*) The synchronous motor is cheaper to build, especially at low speeds, than the induction motor.

(*e*) Its efficiency is generally higher than that of the induction motor.

(*f*) It is specially adapted to high-voltage winding.

The synchronous motor, on the other hand, has several disadvantages, as follows:

(*a*) It is not adapted to work requiring variable speed, as no independent speed regulation is possible.

(*b*) It has small starting torque; hence it is not suitable for work requiring large starting torque, or frequent starting of the load.

(*c*) It has a tendency to "hunt".

(*d*) It requires an exciting current which must be supplied by an outside source.

(*e*) It requires the most skillful and intelligent attention.

A full comparison of the relative advantages of the synchronous motor and the induction motor is given later under the heading "Induction Motor".

Synchronous motors are used where power is required in large amounts, and where the motor does not have to be started and stopped frequently.

Synchronous motors behave differently from direct-current motors. Thus, if the field of a direct-current motor be weakened, the motor will speed up in order to keep the counter-electromotive force at a proper value. But if the field strength of a synchronous motor be changed, the speed cannot change, because the motor must run in synchronism with the alternator that supplies it with current. What then does enable a synchronous motor to adjust itself to changes of load and field strength? It is the change of phase difference between the armature current and the applied electromotive force.

Suppose a synchronous motor running light (*i.e.*, unloaded), and suppose further that there is no friction, hysteresis, or eddy-current loss; then, if this motor be run up to synchronism, and its field adjusted to such a strength that the counter-electromotive force of the motor is equal and opposite to that of the generator, no current will flow through the circuit when the circuit is closed. At any instant the electromotive force that causes current to flow in the circuit is the difference between the instantaneous electromotive force of the alternator and the counter-electromotive force of the motor. On loading the motor, its armature will lag a small fraction of a revolution behind that of the alternator, so that the counter-electromotive force of the motor will no longer be in opposition to that of the alternator. The result is that a current will flow, of a magnitude such as to produce the torque necessary to enable the motor to carry its load. The greater the load on the motor, the greater the lag of its armature, and hence the greater the difference in phase between the applied and the counter-electromotive forces; this, in turn, permits a larger current to flow to supply the additional torque required. If, however, too great a load is put on the motor, the slipping behind of the armature will become sufficiently great to throw the motor out of synchronism, or to cause the motor to "break down", when it will stop. In other words, the motor, under these conditions, cannot exert sufficient torque to handle the load.

71. Starting a Synchronous Motor. If a single-phase alternator be electrically connected to alternating-current supply mains, the machine will not start up and run as a motor, because the current in its armature is rapidly reversing, thus tending to turn the armature first in one direction and then in the other direction in rapid succession. A single-phase alternator which is to be used as a synchronous motor, must be started and brought up to full speed by an engine or other outside source of power.

If a polyphase alternator, on the other hand, is connected to polyphase supply mains, the machine will start and run up to full speed if it has little or no belt load. This self-starting property of the polyphase synchronous motor is explained as follows:

As one of the polyphase currents through the armature of the machine dies away, it leaves a slight amount of residual magnetism in the field-magnet structure if the field magnet is not excited by direct current.

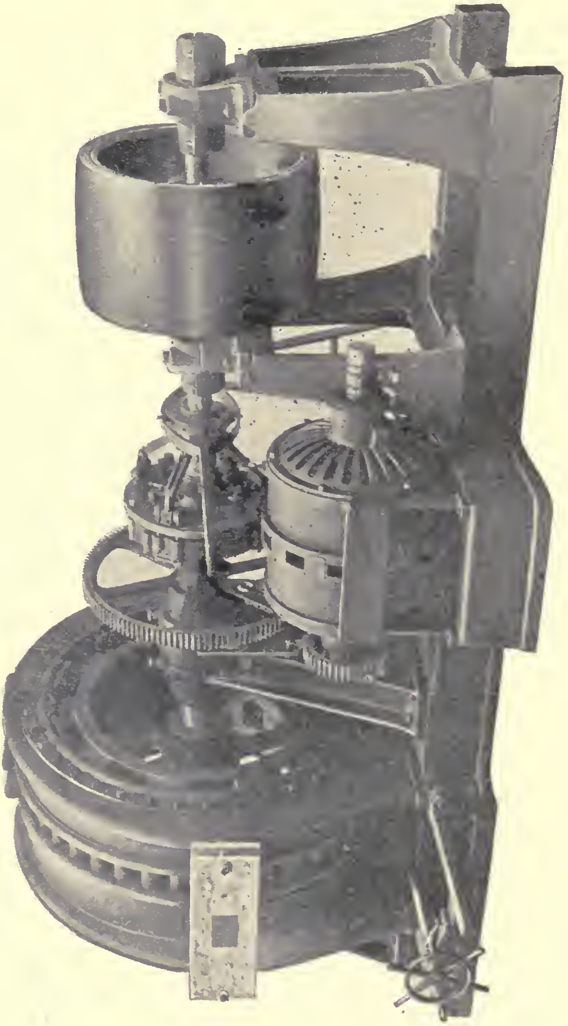


Fig. 174.
Synchronous Motor with Starting Motor.

This residual magnetism acts upon the growing current of the other phase (or phases), and produces a torque tending to turn the armature.

This action of the polyphase alternator is essentially the same as the action of the induction motor.

A polyphase alternator which is to be used as a synchronous motor develops but little starting effort when connected directly to the supply mains, hence it is generally started, especially in larger sizes, by means of a small engine or auxiliary motor, and then thrown into circuit, after which its load is connected to it through a friction clutch, thus allowing it to be thrown on gradually. In smaller sizes the machine is generally self-starting without load, the load being thrown on afterwards. It is necessary always to start up a single-phase motor from some external source whether loaded or unloaded, since it develops no starting torque whatever when thrown in circuit at a standstill.

The exciter of a synchronous motor (a small direct-current dynamo) is usually belted to, or mounted upon, the synchronous motor shaft, so that when the synchronous motor has been brought up to full speed either by separate starting or by self starting, the exciter is in full operation and is in readiness to supply current for exciting the field magnet of the synchronous motor.

Separate Starting of a Synchronous Motor. In the case of the single-phase machine, the power for starting is always derived from a source entirely independent of the single-phase supply. In the case of the polyphase machine, the power for starting is usually developed by a small induction motor supplied with polyphase currents from the mains that supply currents to the synchronous motor itself. The method of separate starting is essentially the same for both single-phase and polyphase machines. The procedure is exactly the same as for starting and adjusting an alternator that is to be connected in parallel with another alternator already in operation. This procedure will be described in detail later.

Fig. 174 is a general view of a 330-kilowatt Stanley (S.K.C.) 2-phase synchronous motor connected to its pulley through a Worrall friction clutch. The small starting motor is a 2-phase induction motor. To start this machine, the load is disconnected by loosening the friction clutch. The small motor is thrown into gear, and then connected to the supply mains. When the large machine has reached synchronous speed, and has been adjusted to the proper phase relation with the electromotive force of the supply mains, it is itself connected to the supply mains. The starting motor is then thrown out of gear, and disconnected from the supply mains; and the load is gradually thrown upon the synchronous motor by means of the friction clutch. In Fig. 174 the synchronous motor, starting motor, pulley, and clutch are shown mounted on one bedplate.

Fig. 175 shows an S. K. C. synchronous motor direct-connected to a direct-current generator, and provided with a small direct-current starting motor. In this case the direct-current generator is left on open circuit while starting, so that but little starting effort is required of the motor. When the synchronous motor and direct-current generator have been brought up to full speed by the small direct-current starting motor, this starting motor is thrown out of gear by means of the lever shown at the extreme left in the figure. This lever moves the large intermediate gear-wheel idler parallel to the armature shaft, and thus disengages the two small spur gears.

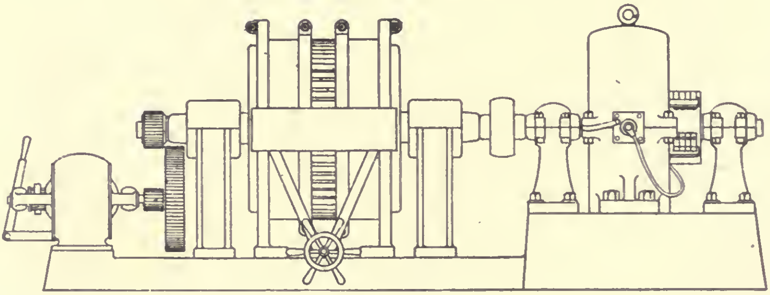
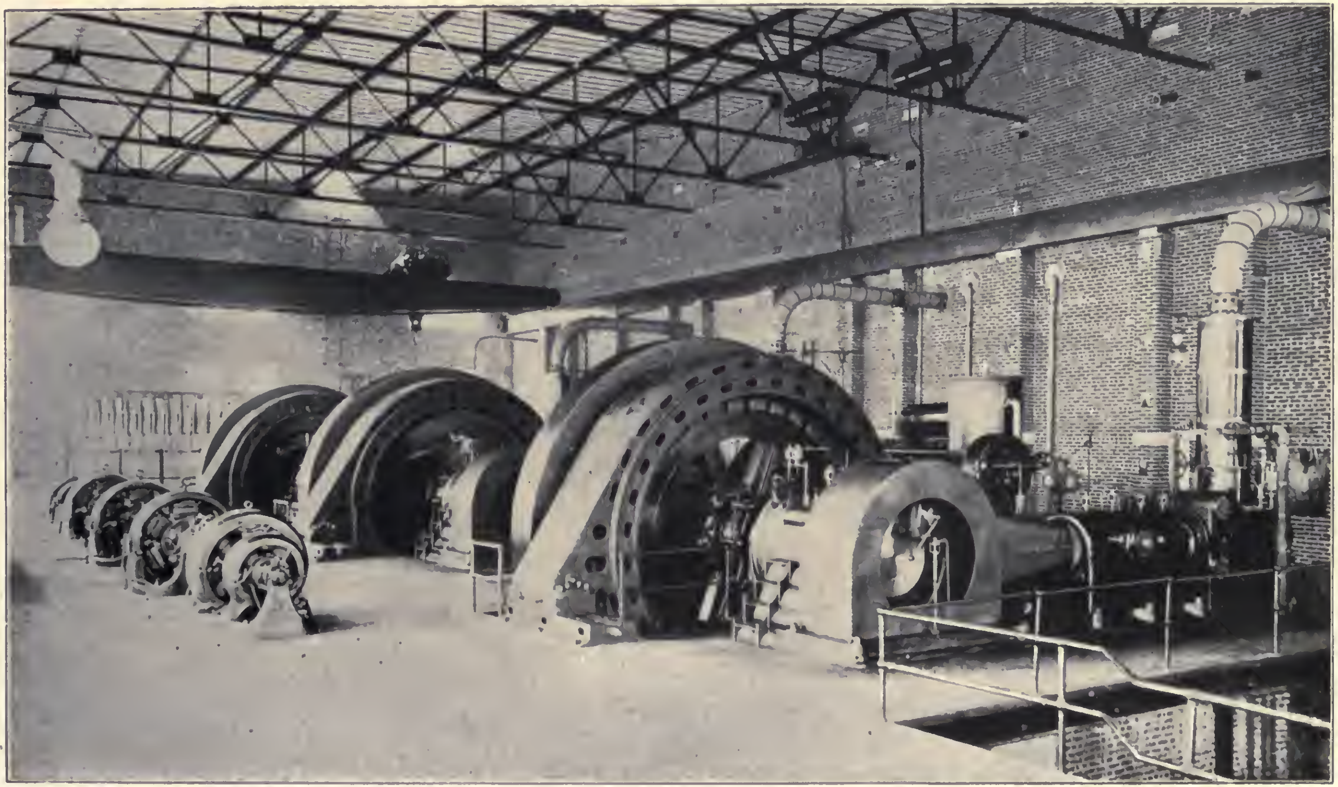


Fig. 175.

The field current for the synchronous motor is taken from the commutator of the large direct-current generator.

Self Starting of a Polyphase Synchronous Motor. In the self-starting of the polyphase synchronous motor, its armature terminals may be connected directly to the polyphase supply mains with its field unexcited. When the machine reaches synchronous speed (driving its exciter), the field is connected to the exciter. The machine is then in full operation as a synchronous motor, and its load may be gradually thrown on, as already described.

The objection to this mode of starting is that the machine takes excessively large lagging currents at starting; and this generally causes a drop in the supply voltage great enough to disturb seriously the general system of distributing mains from which the



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synchronous motor receives its currents. This excessive demand for current at starting is objectionable when the motor takes a large proportion of the generator output, or is used in connection with a lighting service, especially when the motor is started and stopped at frequent intervals.

To avoid an excessive demand for current at starting, an **auto-starter** or **compensator** is frequently employed. The starting compensator for a 2-phase synchronous motor consists of two transformers (three transformers for a 3-phase machine) having their primaries connected across the respective phases of the supply mains, their secondaries being provided with a number of taps so that, at starting, a fraction of the full supply voltage can be applied to the armature terminals of the synchronous motor. This fraction is usually from 40 to 60 per cent of the full voltage; and a switching device is provided by means of which the change from fractional to full voltage can be quickly made when the synchronous motor reaches full speed.

This starting compensator is also used in connection with induction motors, and is fully described subsequently. The transformers used in the starting compensator are, always auto-transformers.

The self-starting of a polyphase synchronous motor (by induction-motor action) depends upon the magnetizing action on the unexcited field magnet poles by the armature currents. Therefore a polyphase alternator having high armature reaction (that is, large magnetizing action on the field for a given armature current, as in the case of an armature with concentrated windings or a machine with small air gaps) will give a large starting torque when used as a self-starting synchronous motor.

Usually less than one minute is required to bring even large synchronous motors to full speed by either method of starting.

At the time of starting, the armature and field windings of a synchronous motor are related to each other as are the primary and secondary of an alternating-current transformer. The result is, that when the field coils have many turns of wire, a dangerously high electromotive force may be induced in them.

This production of high voltages in the field coils of a self-started polyphase synchronous motor may be, to a great extent avoided, by using few turns of large wire in the field winding, thus necessitating the use of a low voltage exciter. For this reason exciters giving an electromotive force as low as 50 volts are frequently used. Another method of obviating the danger referred to, is to provide short-circuited metal rings around the field poles. These rings limit the changes of magnetism in the pole-pieces, and thereby prevent the formation of excessively high induced voltages in the field coils.

In synchronous motors of the stationary field type, the field circuit may be broken up into many separate parts so as to divide up the induced electromotive force. Thus, Fig. 176 shows the stationary field of an alternator (synchronous motor) with the terminals of each field spool brought out to convenient switches o the frame of the machine. During starting these switches are open, and when the machine has reached synchronous speed they are all closed, thus connecting all the field spools in series to the exciter.

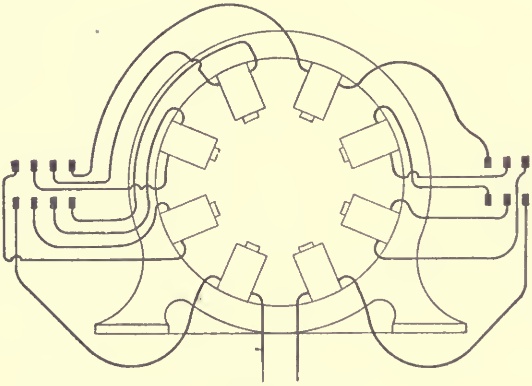

Fig 176.

72. Hunting Action of the Synchronous Motor. When the load on a synchronous motor is suddenly increased, the motor slows down momentarily and falls behind the generator in phase. When the motor has fallen behind sufficiently to take in power enough to enable it to carry its load, it is still running slightly below synchronism; it therefore falls still further behind, and takes an excess of power from the generator which quickly speeds it above synchronism. It then gains on the generator in phase until it is taking in less power than is required for its load, when it again slows down, and so on. This oscillation of speed above and below synchronism, called hunting, is accompanied with great changes in the current supplied to the synchronous motor, and with rapid rise and fall of the electromotive force between the terminals of the motor. It is frequently a source of great annoyance, especially where several synchronous motors (or rotary converters) are run in parallel from the same mains.

Hunting is frequently produced by the periodic changes in the speed of the engine that drives the generator. Thus the engine momentarily increases its speed as the steam acts upon the piston at each stroke, and diminishes its speed in the intervals between the strokes.

Hunting is prevented by the use of heavy copper frames or dampers partly covering the edges of the pole-pieces of the field magnet both in the generator and in the synchronous motor.

The hunting of a synchronous motor is a phenomenon of the same nature as the hunting of a steam engine having an over-sensitive governor. When the load on the engine is suddenly increased, the engine slows down momentarily, causing the governor to admit more steam than is needed for the increased load. The result is that the engine quickly speeds up, causing the over-sensitive governor to shut off too much steam, so that the engine slows down again, and so on.

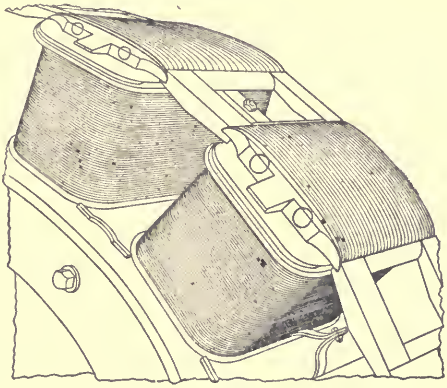
Fig. 177.

Fig. 177 is a view of a portion of the revolving field of an alternator, showing the copper dampers,* consisting of rectangular frames, driven into place under the overhanging tips of two adjacent poles. There is one of the dampers provided between each pair of adjacent poles, all around the field.

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* Formerly used by the Bullock Electric Mfg. Company. They have recently abandoned this design as the construction of their alternators is such as to render it unnecessary.

73. Torque and Power Output of a Synchronous Motor. A given synchronous motor operating with given applied voltage is capable of developing a definite maximum torque (or of delivering a definite maximum amount of power). An attempt to take more than this maximum power from the machine, causes the machine to fall out of step (that is, out of proper phase relation) with respect to the supply voltage; and the motor accordingly stops. A properly designed synchronous motor will, however, carry a reasonable overload before reaching the above-mentioned maximum at which the machine stops.

The maximum power that can be delivered by a synchronous motor is greatly increased by increase of the applied voltage, and greatly decreased by a decrease of the applied voltage. In fact the maximum power output is proportional to the square of the applied voltage; therefore, the voltage of supply should never be allowed to fall much below the normal or rated value.

74. Field Excitation and Power Factor. While the power factor of a non-synchronous (induction) alternating-current motor is fixed by its design, and its current is always lagging behind the applied electromotive force, the current delivered to a synchronous motor may be made either lagging or leading at will. This remarkable control of the phase of the current is accomplished by varying the strength of the field excitation.

An increase in the field excitation of a synchronous motor will cause a corresponding increase in the counter-electromotive force generated in the motor armature. By properly adjusting the field excitation, this counter-electromotive force of the motor can be made considerably greater than the electromotive force applied at the motor terminals. The result is that an increased but leading current (that is, one ahead of the applied voltage, as in a condenser) flows in the armature. On the other hand, a field excitation below the normal amount produces an increased but lagging current (that is, one behind the applied voltage, as in an inductance coil). If the field excitation is normal, that is, of such a value that the current in the motor armature is exactly opposed in phase to the counter electromotive force (power factor, unity), then the effective value of this current will be a minimum; and hence the efficiency of the motor, generator, and transmission lines will be a maximum because the $I^2 R$ losses will be a minimum.

Considered simply as a motor, without reference to the transmission system as a whole, the most efficient point of operation is with unity power factor, or, in other words, with a field excitation which will make the armature current a minimum.

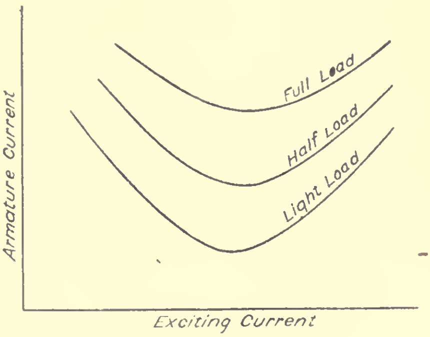

Fig. 178.

The effect upon the armature current, produced by varying the field excitation, is shown by the curves in Fig. 178. Up to a certain point, as the excitation is increased, the armature current is lagging, and decreases to a minimum value. Further increase of the exciting current causes the armature to take more current, which is now ahead of the applied electromotive force in phase, that is, is now leading. There is one value of the exciting current for which the armature current is a minimum. In motors of good regulation this value of the exciting current varies but slightly with different loads.

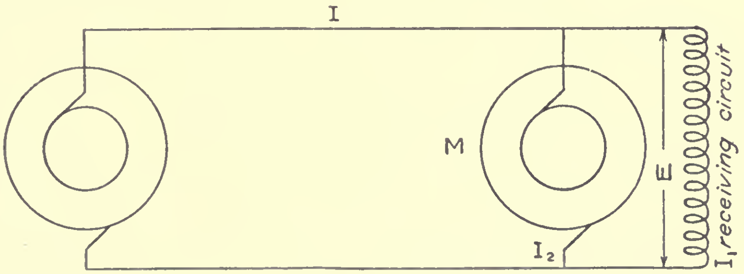

Fig. 179.

75. Use of a Synchronous Motor as a Condenser. A Synchronous motor with its field magnet over-excited takes a current which is ahead of the applied electromotive force in phase. Such a machine may therefore be connected across the terminals of an inductive receiving circuit, as shown in Fig. 179, so as to compensate for lagging current delivered to the receiving circuit, thus reducing the line current to the lowest value that will suffice to transmit the power taken by the receiving circuit. The clock diagram (Fig. 180) shows how the leading current I_2 taken by the synchronous motor M (Fig. 179) gives, when combined with the current I_1 delivered to the receiving circuit, a resultant line current I, which is in phase with the electromotive force E between the mains.

A synchronous motor used primarily for compensating the lagging current delivered to an inductive receiving circuit, is called a rotary condenser or a synchronous compensator. The rotary condenser is especially useful when induction motors or lightly loaded transformers or both, are supplied over a long transmission line. In such cases the reduction of the line current to the smallest possible value effects considerable saving in the matters of power losses in the transmission line. The use of a rotary condenser is also an advantage in that the regulation of voltage at the receiving end of the transmission line is improved.

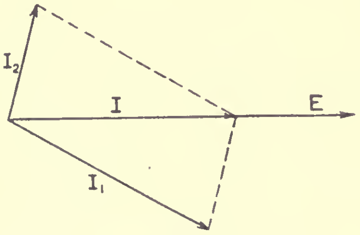

Fig. 180.

A given synchronous motor is most effective as a rotary condenser when it is not required to deliver any mechanical power as a motor, that is, when it is run at zero load. When a synchronous motor is to be used to deliver mechanical power, as well as to take a leading current for the purpose of compensating the lagging current taken by the inductive receiving circuit, it is customary to limit the load on the motor to 70.7 per cent of its full-load rating (that is, its rating if it were to be used as a motor only, and not as a rotary condenser). When the motor takes in its full-load rated current, but only 70.7 per cent of its full-load rated power, its field being over-excited, then its current is 45° ahead of the electromotive force; the power factor of the motor is 70.7 per cent; the power component of the current (that is the component which is in phase with the supply electromotive force) is 70.7 per cent of the full current; and the wattless component of the current (the component which is 90° ahead of the supply electromotive force in phase) is also 70.7 per cent of the full-load current.

Example. A synchronous motor rated at 100 kilowatts at 1,000 volts would have a full-load rated current of 100 amperes, the field of the machine being excited to give unity power factor. If this machine is to be operated as a rotary condenser, its field excitations will have to be increased. If the machine is to carry a load of 70.7 kilowatts, and at the same time to take as large a leading wattless current as possible (without, however, exceeding the full-load rated current of 100 amperes), then the field will have to be over-excited to such an extent as to cause the machine to take its full rated current of 100 amperes at 70.7 kilowatts load. In this case the power component of the 100-ampere current will be 70.7 amperes; the wattless component of the 100-ampere current will be 70.7 amperes $[100 = \sqrt{(70.7)^2 + (70.7)^2}]$; and the power factor of the over-excited motor will be 70.7 per cent.

76. Characteristic Curves and Tests. The difference between a synchronous motor and an alternating-current generator consists mainly in the method of operating; any alternator will run as a synchronous motor, and *vice versa.* Therefore all the tests described in articles 61 to 66, with reference to alternators, may be applied in a similar manner to synchronous motors. In making a heat test on a small synchronous motor, it is usually run at full load as a motor.

In the case of large synchronous motors, the "heat-run" or test is usually made by running the machine as a generator on short circuit, with a portion of its field coils connected in opposition, as described in article 65 on the heat test of alternators.

The efficiency of a synchronous motor is calculated in the same manner as that of an alternator (see article 67).

77. Phase Characteristic. Regulation for alternators, as described in article 64 is not calculated in the case of a synchronous motor; but the determination of the "phase characteristic" of a synchronous motor corresponds to, and is substituted for, the regulation test. A "phase characteristic" is a curve showing the relation between the armature current and the field current of a synchronous motor, the test being carried out under constant conditions with respect to voltage, frequency, and load. Phase characteristics are shown in Fig. 178.

Phase characteristics are usually taken at no load, although it not infrequently happens that it is desired to obtain a phase characteristic at full load. To make the test at no load, it is simply necessary to run the motor unloaded, supplying alternating currents of the proper voltage and frequency to the armature terminals of the motor. The field current is then varied by successive steps, both above and below its normal value, until the armature current has attained rated full-load value, both for leading and for lagging current. For each value of the field current, simultaneous observations are made of the amperes in the armature, the volts supplied to the armature terminals, the amperes in the field, and the speed. The normal field current is that value for which the armature current has the lowest value.

If a phase characteristic at full load is desired, the most convenient way of loading the motor is to cause it to drive a direct-current generator of known efficiency, by means of a belt connecting their respective pulleys. The power output of the direct-current generator can be accurately measured by means of an ammeter and a voltmeter. Knowing the output, and the efficiency of the direct-current generator at any output, the mechanical *input* (that is, the $\frac{\text{output}}{\text{efficiency}}$) to the generator can be calculated. This input to the generator is evidently equal to the mechanical output of the synchronous motor, the power lost in the belting being negligible.

The load on the motor must be kept constant throughout the test. The armature current for a full-load phase characteristic cannot be varied through such a wide range of values as at no load, owing to the inability of the armature windings of the motor to carry the excessive current without over-heating.

78. Pulsation Test. This test is to determine whether or not the synchronous motor has a decided tendency to hunt. For this test the synchronous motor is supplied with alternating current or currents from a very steadily driven alternator over an "artificial transmission line". This "artificial line consists simply of a resistance equal to the resistance* of the transmission line over which the synchronous motor is to be supplied with current when finally installed.

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*NOTE. Usually the transmission line has a resistance such as to give a 10 per cent drop of electromotive force when full-load current is delivered to the motor.

The synchronous motor is driven at zero load, taking current through the artificial line, the tendency to hunt being greatest at zero load. The connections are the same as in the test for phase characteristic. The hunting action is indicated by the pulsation of the ammeters and voltmeters. The field current of the motor is varied from considerably below to considerably above rated full-load field current. For each value of the field current, the indications of the instruments are carefully observed. The pulsations of the instruments are noted.

During this test, care must be taken that the alternator supplying the power to drive the motor under test, does not pulsate, for, if it does, the pulsations of the instrument pointers would not then give a reliable indication of the performance of the motor itself under normal working conditions.

79. Break-down Test. As its name implies, this test is to determine the maximum power that a synchronous motor will deliver at its pulley, before falling out of synchronism and stopping. As in the case of the full-load phase characteristic, the power output of the motor is most conveniently absorbed and measured by belting the motor to a direct-current generator, and measuring the electrical output of this generator. For further description and details of the break-down test, the reader is referred to the article on the break-down test for induction motors.

80. Self-Starting Test. The object of a starting test on a synchronous motor is to determine:

(*a*) The voltage and current required to start the motor.

(*b*) The time required for the motor to reach synchronous speed (synchronism).

(*c*) The electromotive force induced in the field magnet windings at the instant of starting.

The starting test is made on polyphase motors only, for, as previously stated, single-phase synchronous motors are not inherently self-starting, but must even in the smaller sizes, be provided with special starting devices.

The synchronous motor to be tested is connected to mains supplying alternating currents of the proper frequency. Arrangement is made to adjust the voltage applied to the armature terminals of the motor, by means of potential (voltage) regulators connected in the armature circuits between the supply mains and the armature terminals. An ammeter is connected in series with each phase winding of the armature; that is, two ammeters are needed for a two-phase motor, and three ammeters for a three-phase motor. A voltmeter is connected to the terminals of the secondary coil of a small step-down potential transformer the primary coil of which is connected to the terminals of the field winding of the motor. A voltmeter is also connected between the supply mains.

The test is made with no current in the field and the field circuit open.* The voltage applied to the armature terminals is slowly increased until the motor starts to revolve. At the instant that the motor starts, the readings of all the instruments are recorded as per the following tabular form:

Volts between armature terminals.	Amperes in the armature. (Each phase.)	Volts induced in field windings.

After the motor starts, the voltage applied to the armature terminals is kept constant; and the time required for the motor to attain synchronous speed, reckoned from the instant it starts, is observed. The exact instant that synchronism is reached, is indicated by violent swings of the pointers of the ammeters as well as those of the voltmeters connected to the armature terminals. At synchronism, another set of observations is taken.

This procedure is repeated for a series of initial positions of the armature, the object being to find the most unfavorable position of the armature and the corresponding starting current, and the time required to reach synchronous speed from this most unfavorable position.

The series of initial positions of the armature are chosen as follows:

The circumference of the armature between the centers of two adjacent field poles is divided into a number of equal parts, this number not being a multiple of the number of phases, nor of the number of slots per pole per phase; usually there are seven parts. The starting positions thus chosen will include every possible position that a magnet pole may have relative to an armature slot. These parts are marked by chalked lines, and the various starting positions of the armature relative to the field magnet poles are determined by setting each of the marks in succession into coincidence with a given field pole tip.

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*NOTE. The primary of the potential transformer takes but little current, and the field circuit, to all intents and purposes, is open.

THE TRANSFORMER.

81. The **transformer** consists of two separate and distinct coils of wire insulated from each other, and wound upon one and the same laminated iron core. Fig. 217 shows a sectional view of a common commercial type of transformer.

In practice, one of the coils receives alternating current from a high- (or low-) voltage source of supply; and the other coil delivers alternating current to a receiving system at a low (or high) voltage. When the transformer receives alternating current at high voltage and delivers it at low voltage, we have what is called **step-down transformation;** when the transformer receives alternating current at low voltage and delivers it at high voltage, ws have what is called **step-up transformation.**

The coil of a transformer which receives alternating current from a source of supply, is called the **primary coil;** and the coil which delivers alternating current is called the **secondary coil.**

In Fig. 217, each limb of the core is wound with half of the secondary coil (coarse wire) next to the core, and with half of the primary coil (fine wire) over the secondary.

The alternator, as we have already seen, is a machine in which an alternating electromotive force is produced by the cutting of a permanently established magnetic flux by wires on account of the motion of the flux relative to the wires.

The transformer, on the other hand, is an arrangement whereby an alternating electromotive force is produced in a stationary coil of wire (secondary) by reversals of magnetic flux through a stationary iron core, these reversals of flux being produced by alternating current supplied to the primary coil of the transformer.

82. Physical Action of the Transformer. *Without Load.* When the secondary of a transformer is on open circuit, it can of course, deliver no current; and the transformer is said to be operating at **zero load.** Under these conditions, only a small amount of alternating current flows through the primary coil. This current causes repeated reversals of magnetic flux through the iron core. These reversals of magnetic flux induce electromotive forces in both coils. The electromotive force thus induced in the primary coil is opposite in direction, and very nearly equal, to the electromotive force applied to the primary coil. Only the difference between the applied electromotive force and the opposing induced electromotive force is available for producing current through the primary coil; and since this difference is small, the primary current is small at zero load. The primary current at zero load is called the **no-load current** of the transformer.

With Load. Whether the secondary coil of a transformer is delivering current or not, the reversals of magnetic flux in the transformer core always induce an alternating electromotive force in the coil. When alternating current is taken from the secondary of a transformer, the transformer is said to be **loaded.** The action of this secondary current as it flows through the secondary coil, is to oppose the magnetizing action of the slight current already flowing in the primary coil, thus decreasing the maximum value reached by the alternating magnetic flux in the core, and thereby decreasing the induced electromotive forces in both coils. The amount of this decrease, however, is *very small*, inasmuch as a very small decrease of the induced electromotive force in the primary coil greatly increases the difference between the electromotive force applied to the primary coil and the opposing electromotive force induced in the primary coil, so that the primary current is greatly increased. In fact, *the increase of primary current due to the loading of the transformer is just great enough (or very nearly) to exactly balance the magnetizing action of the current in the secondary coil;* that is, the flux in the core must be maintained approximately constant by the primary current whatever value the secondary current may have.

83. Electromotive Force and Current Relations in a Transformer. *Electromotive Force Relations.* The electromotive forces induced in the respective coils of a transformer are proportional to the number of turns of wire in each; and from the above discussion it is evident that the electromotive force induced in the primary coil is sensibly equal to the supply electromotive force, whether the transformer is loaded or not. Therefore

$$\frac{E'}{E''} = \frac{Z'}{Z''} \qquad (31)$$

in which E′ is the electromotive force applied to the primary, E″ is the electromotive at which the secondary coil delivers alternating current, Z′ is the number of turns of wire in the primary coil, and Z″ is the number of turns of wire in the secondary coil.

Current Relations. The magnetizing action of the primary current I′ of a transformer having Z′ turns of wire in its primary coil, may be expressed by the product Z′I′, that is, by ampere-turns; and similarly, the magnetizing action of the secondary current I″ may be expressed by the product Z″I″, where Z″ is the number of turns of wire in the secondary coil. Therefore since the magnetizing actions of the two coils are equal (and opposite), we have:

$$Z'I' = Z''I'',$$

or

$$\frac{I'}{I''} = \frac{Z''}{Z'}, \qquad (32)$$

in which Z′ and Z″ are the turns of wire in the respective coils; I″ is the current delivered by the secondary coil; and I′ is the increase of current taken by the primary coil over and above the no-load current, due to the fact that the secondary coil is delivering current.

Now, in most commercial transformers the no-load current is quite small; and, neglecting this current entirely, the only current in the primary coil would be the increase of primary current due to the fact that the secondary coil is delivering current. Therefore equation 32 expresses, with sufficient accuracy for most purposes, the relation between the actual primary current I′ and the secondary current I″.

84. Summary of Electromotive Force and Current Relations in a Transformer. A transformer which delivers current I″ to a receiving circuit, takes an amount of current equal to $I'' \times \frac{Z''}{Z'} (= I')$ from the source of supply. The electromotive force of the source of supply is E′, and the electromotive force at which the secondary delivers current is equal to $E' \times \frac{Z''}{Z'} (= E'')$.

Example. A certain transformer rated at $5\frac{1}{2}$ kilowatts has 660 turns of wire in its primary coil and 66 turns of wire in its secondary coil. The primary coil is connected between 1,100-volt supply mains. Therefore the secondary electromotive force, by equation 31 is:

$$E'' = \frac{Z''}{Z'} \times E' = \frac{66}{660} \times 1{,}100 = 110 \text{ volts.}$$

If ten lamps, each taking half an ampere, are connected to the secondary coil, the secondary current will be 5 amperes; and the primary current, by equation 32 will be:

$$I' = \frac{Z''}{Z'} \times I'' = \frac{66}{660} \times 5 = .5 \text{ ampere.}$$

The power delivered to the lamps by the secondary coil is equal to E″ I″, since the lamp circuit is non-inductive. That is:

Power delivered to lamps = 110 volts × 5 amperes = 550 watts. The power delivered to the primary coil in this case (non-inductive secondary circuit), is equal to E′ I′. That is:

Power delivered to primary = 1,100 volts × 0.5 amperes = 550 watts.

If 100 lamps, each taking half an ampere, are connected to the secondary coil, the secondary current will be 50 amperes, and the primary current will be 5 amperes; the power delivered to the lamps will be 5,500 watts, and the power delivered to the primary coil will also be 5,500 watts.

The above calculations ignore the following actions which take place in an actual transformer:

(*a*) Losses of electromotive force in overcoming the resistances of primary and secondary coils.

(*b*) Losses of power (I^2R) in the primary and secondary coil;

(*c*) Loss of power in the iron core, due to hysteresis and eddy currents

85. Automatic Action of the Transformer. When the load on a transformer is increased, the primary of the transformer automatically takes additional current and power from the supply mains in direct proportion to the load on the secondary. When the load on the secondary is reduced, for example by turning off lamps, the power taken from the supply mains by the primary coil is automatically reduced in proportion to the decrease in the load. This automatic action of the transformer is due to the balanced magnetizing action of the primary and secondary currents; and it is illustrated in the above example.

86. Comparison of the Actual with the Ideal Transformer. The foregoing discussion of electromotive force and current relations in a transformer is based upon the following assumptions:

(*a*) That the no-load current of the transformer is negligible, and that it represents no power taken from the supply mains; or, in other words, that eddy-current and hysteresis losses are absent.

(*b*) That the resistance of the coils is negligible, so that the electromotive force applied to the primary coil is wholly balanced by the opposing electromotive force in the primary coil, and so that the whole of the electromotive force induced in the secondary coil is available at the terminals of that coil.

(*c*) That all the magnetic flux which passes through the primary coil passes through the secondary coil also; or, in other words, that there is no *magnetic leakage*.

A transformer that would meet these conditions would be an ideal transformer. A well-designed transformer operating on moderate load does approximate quite closely to the ideal transformer in its action; and equations 31 and 32 are much used in practical calculations. For some purposes, however, it is desirable to consider the action of the transformer, taking account of coil resistances, of eddy currents and hysteresis, and of the fact that some lines of magnetic flux pass through one coil without passing through the other (magnetic leakage). The extent to which a well-designed transformer deviates from an ideal, is exemplified by the following actual results obtained with the $5\frac{1}{2}$-kilowatt transformer used in the example of the preceding article:

At no load, the value of E'' is 109.8 volts; the no-load current is 0.129 amperes; and the power taken from the mains by this no-load current (core loss) is 100 watts. This core loss is nearly constant at all loads.

When 100 lamps, taking 50 amperes of current, are connected to the secondary, then E'' is 107.2 volts. The RI^2 loss in the primary coil is 65 watts; and the RI^2 loss in the secondary is 65 watts. Therefore the power delivered to the lamps is 5.36 kilowatts; the power taken from the supply mains is $5{,}360 + 100 + 65 + 65$, which is equal to 5,590 watts; and the full-load efficiency of the transformer is 96 per cent.

87. Maximum Core Flux. In the designing of transformers and in the predetermination of core loss, it is necessary to calculate the maximum value reached by the alternating magnetic flux through the transformer core. This maximum value of the core flux may be easily and accurately calculated by means of the following formula for a harmonic (that is, sine-wave) electromotive force:

$$\Phi = \frac{E' \times 10^8}{4.44 \times Z \times f}, \qquad \textbf{(33)}$$

in which Φ is the maximum value of the core flux, and is equal to the product of maximum flux density and sectional area of the core ($= \mathscr{B}A$); E′ is the effective value of the electromotive force applied to the primary coil; Z' is the number of turns of wire in the primary coil; and f is the frequency of the applied electromotive force, in cycles per second.

Derivation of Equation 33. Consider the instant when the core flux is at its maximum positive value Φ. After a quarter of a cycle, or after $\frac{1}{4f}$ second, the flux is reduced to zero. The average rate of change of the flux during this quarter of a cycle, is equal to:

$$\frac{\text{total change of flux}}{\text{elapsed time}} = \frac{\Phi}{\frac{1}{4f}} = 4f\Phi$$

which is equal to the *average* electromotive force (in c.g.s. units) induced in each turn of wire in the primary coil. Therefore the total electromotive force induced in the Z' turns of wire in the primary coil, is $4f\Phi Z'$ c.g.s. units, or $4f\Phi Z' \div 10^8$ volts, since 10^8 c.g.s. units equal 1 volt.

This average value of the induced electromotive force is equal (very nearly) to the average value of the electromotive force applied to the primary coil; and it must be multiplied by the form factor* of the electromotive force curve to give the effective value E′ of the applied electromotive force. The form factor of a sine-wave electromotive force is 1.11. Therefore

$$E' = 1.11 \times \text{average value} = 4.44 f\Phi Z' \div 10^8 \text{ volts.}$$

Hence, solving for Φ, we have equation 33 at once.

Example. In the $5\frac{1}{2}$-kilowatt transformer used as an illustration in Articles 84 and 86, there are 660 turns of wire in the primary coil, that is $Z' = 660$. This primary coil is connected to

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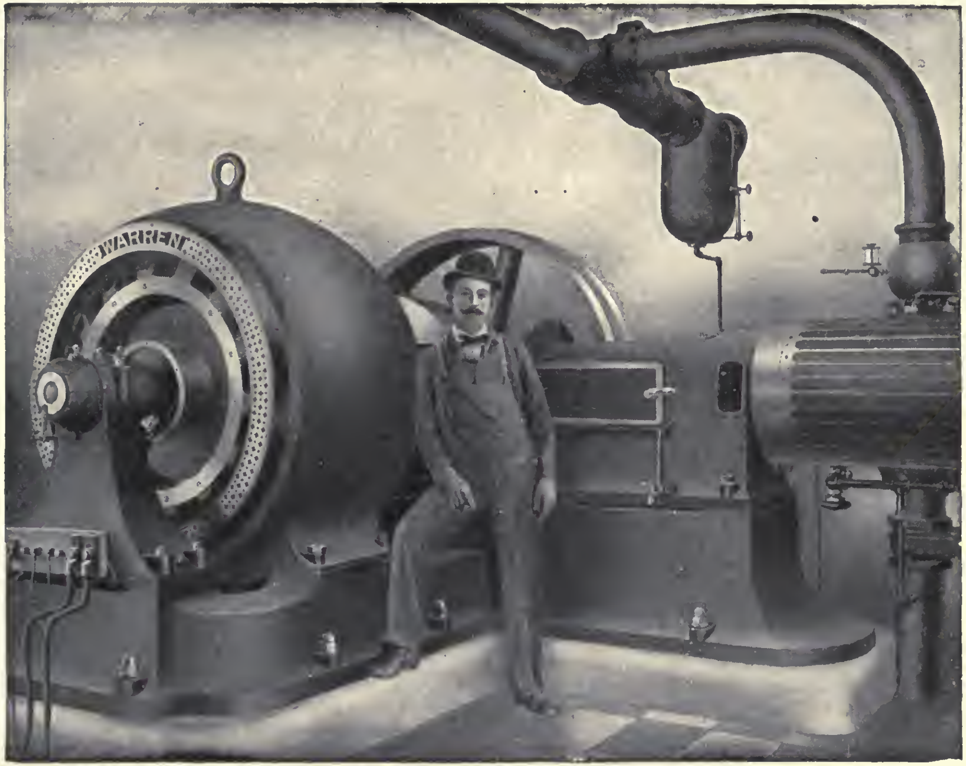
*(See Article 8.)



150 K.W. WARREN ALTERNATOR.

Engine Type.

alternating-current supply mains so that the electromotive force applied to the primary coil is 1,100 volts (effective). The frequency of the electromotive force is 125 cycles per second ($=f$). In the assumption that the electromotive force wave is a sine curve, we have, using equation 33:

$$\Phi = \frac{1,100 \text{ x } 10^8}{4.44 \times 660 \times 125} = 300,000 \text{ lines of magnetic flux.}$$

This is the maximum value of the alternating magnetic flux in the transformer core.

The cross-sectional area A of the transformer core is $15\frac{1}{2}$ square inches, so that the maximum value of the magnetic flux-density in the core is

$$\frac{\Phi}{A} = \frac{300,000}{15\frac{1}{2}} = 19,350 \text{ lines per square inch.}$$

This is equivalent to a flux-density of 3,000 lines per square centimeter. Flux-density in lines per square centimeter is usually represented by the letter $\mathcal{B}$.

88. Ideal Transformer Action Graphically Represented. Case a. *Without Load.* The line OΦ in the clock diagram, Fig. 181, represents the alternating magnetic flux in the core of a transformer, the line OE′ represents the electromotive force applied to the primary coil, and the line OE″ represents the electromotive force induced in the secondary coil. When the transformer is at zero load, the current in the primary coil, I_O, (the no-load current) lags greatly behind the applied electromotive force E′, as shown in the figure, in which the line OI_O represents the no-load current. The electromotive forces induced in both primary and secondary coils are 90° behind the core flux, OΦ, in phase, and the electromotive force OE′ applied to the primary coil, being at each instant opposite to the electromotive force induced in the primary, is 90° ahead of OΦ in phase.

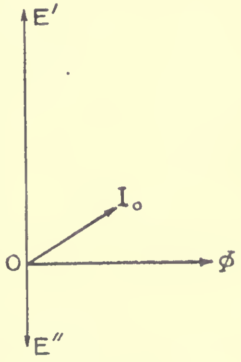


Fig. 181.

Case b. *With Load, Receiving Circuit Nearly Non-Inductive.* The lines $O\Phi$, OE', OE'', and OI_0 in Fig. 182 represent alternating core flux, primary applied electromotive force, secondary induced electromotive force, and no-load current, exactly as in Fig. 181. The line OI'' represents the secondary current lagging slightly behind the secondary electromotive force OE''; and the line OA represents the increase of primary current due to the loading of the transformer. The total primary current is represented by the line OI', which is the vector (or geometric) sum of OA and OI_0. The current OA is exactly opposite to OI'' in phase; and the product of this current OA and the primary turns Z' balances the magnetizing action $Z''I''$ of the secondary current. As is evident from Fig. 182, the loading of a transformer (non-inductive load) not only increases the value of the primary current, but reduces its angle of lag behind the primary applied electromotive force. Thus, at zero-load the primary current is OI_0; and when the transformer is loaded (non-inductive load) the primary current becomes OI'.

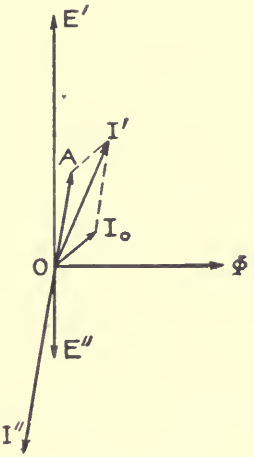


Fig. 182.

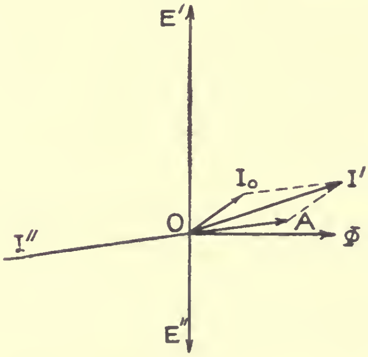


Fig. 183.

Case c. *With Load, Receiving Circuit Highly Inductive.* In Fig. 183 the line OI'' represents the current delivered by the secondary coil of a transformer to a highly inductive receiving circuit; the line OA represents the increase of primary current due to the load; and OI' represents the total primary current. In this case, also, the part OA of the primary current is exactly opposite in phase to the secondary current OI''.

ALTERNATING CURRENT MACHINERY.

PART IV.

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89. Influence of Coil Resistances and Magnetic Leakage Graphically Represented. The discussion given in the foregoing article takes account of the no-load current of a transformer. This no-load current is the only factor that affects the ideal relation (equation 32) between primary and secondary currents in a transformer. Coil resistances and magnetic leakage are, on the other hand, the only things that affect perceptibly the ideal relations (equation 31) of primary and secondary electromotive forces.

Magnetic leakage is equivalent, in its effect upon the action of a transformer, to an outside inductance (a choke coil) connected in series with the primary coil. Let L′ be this inductance (in henrys) which is equivalent to the magnetic leakage of a transformer. Then ω L′ (ω equals 2π times the frequency) is the reactance (in ohms) of this inductance.

The effects of coil resistances and magnetic leakage upon the ideal relation between E′ and E″, are shown in the clock diagram, Fig. 184.

The total electromotive force OE′ applied to the primary coil is used (*a*) to overcome the resistance R′ of the primary coil; (*b*) to overcome the electromotive force induced in the primary coil by the leakage flux; and (*c*) to balance the electromotive force induced in the primary coil by the magnetic flux OΦ, which passes through both coils.

The part (*a*) of OE′ is equal to R′I′, and it is in phase with I′. The part (*b*) of OE′ is equal to ωL′I′, and it is 90° ahead of I′ in phase. The part (*c*) of OE′ is represented by the line OA′. The total electromotive force induced in the secondary coil is equal to OA′ $\times \frac{Z''}{Z'}$. This electromotive force is represented by the line OB. A portion of this total induced electromotive force OB is used to overcome the resistance R″ of the secondary coil; and the remainder OE″ is available at the terminals of the secondary coil to force current through the secondary receiving circuit

From Fig. 184 it is evident that the ratio $\frac{E''}{E'}$ is less than its ideal value $\frac{Z''}{Z'}$ $(=\frac{OB}{OA'})$ because of the "resistance loss" R′I′ of electromotive force in the primary coil, because of the "leakage loss" L′I′ of electromotive force in the primary coil, and because of the "resistance loss" R″I″ of electromotive force in the secondary coil.

Transformer Regulation with Non-inductive Load. When a transformer secondary delivers current to a non-inductive circuit, then OI″ Fig. 184 is parallel to OB, and OI′ is nearly parallel to OE′, so that R′I′ is nearly parallel to OE′, and ωL′I′ is nearly at right angles to OE′. Therefore the difference in value between OE′ and OA′ is nearly equal to R′I′, and nearly independent of ωL′I′. Therefore the falling off E″ of secondary voltage, with increase of load, is due almost wholly to R′I′ and to R″I″ when the receiving circuit is non-inductive, and is not due, to any perceptible extent, to magnetic leakage.

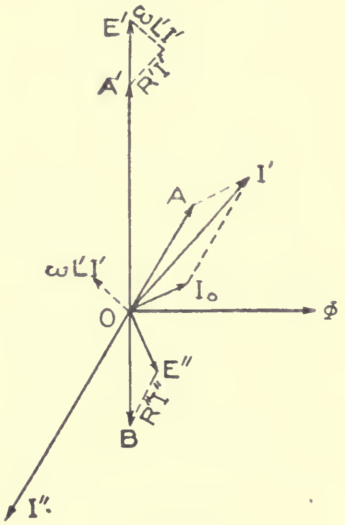

Fig. 184.

Transformer Regulation with Highly Inductive Load. When a transformer secondary delivers current to a highly inductive circuit, then OI″, Fig. 184, is nearly at right angles to OB, and OI′ is nearly at right angles to OE′ so that R′I′ is nearly at right angles to OE′; ωL′I′ is nearly parallel to OE′, and further, R″I″ is nearly at right angles to OB. Therefore the difference in value between OE′ and OA′ is nearly equal to ωL′I′, and nearly independent of R′I′, while OB is nearly equal to OE″. Therefore the falling off E″ of secondary voltage, with increase of load, is due chiefly to ωL′I′ (that is, to magnetic leakage) when the receiving circuit is highly inductive, and is not due to any great extent to coil resistances.

Example. The primary of a certain 10-kilowatt (1,000-volt : 100-volt) transformer has a resistance of 1.5 ohms, and the secondary coil has a resistance of 0.015 ohms. The secondary coil delivers 100 amperes to a non-inductive receiving circuit; and, ignoring no-load current, the primary takes 10 amperes from 1,000-volt mains. The RI loss of electromotive force in the primary coil is therefore 1.5 ohms × 10 amperes = 15 volts, so that the portion OA′, Fig. 184, of the primary applied voltage is very nearly 1,000 − 15 = 985 volts. Therefore the total electromotive force OB induced in the secondary coil is $\frac{Z''}{Z'} \times 985$ volts $= 98.5$ volts. The RI loss of electromotive force in the secondary coil is 0.015 ohms × 100 amperes = 1.5 volts, so that the electromotive force between the terminals of the secondary coil is 98.5 volts − 1.5 volts, or 97 volts. In this case, the secondary receiving circuit is non-inductive, and the portion $\omega L'I'$ of the primary applied voltage is nearly at right angles to E′. This loss of voltage $\omega L'I'$ has therefore no appreciable effect in lessening the value of the available part OA′ of the primary applied voltage E′.

The leakage reactance $\omega L'$ of the above transformer is 5 ohms. If the secondary coil delivers 100 amperes of current to a very highly inductive receiving circuit, then this 100 amperes is nearly 90° behind OB, Fig. 184, in phase; and the primary current of 10 amperes is nearly 90° behind OA′ in phase. Therefore the leakage voltage loss $\omega L'I'$, which is equal to 50 volts, is nearly parallel to OA′, so that OA′ is very nearly equal to 1,000 volts − 50 volts, or 950 volts, and E″ is very nearly equal to $\frac{Z''}{Z'} \times 950$ volts, or 95 volts. In this case, $R'I'$ and $R''I''$ are nearly at right angles to OA′ and OB, and these resistance losses of voltage do not have an appreciable effect in lessening the secondary terminal voltage E″.

The above discussion of the effects of coil resistances and of magnetic leakage shows that the ratio of E′ and E″ is very nearly equal to its ideal value $\frac{Z'}{Z''}$ when the primary and secondary currents of a transformer are small, that is, when the load on the transformer is zero.

TRANSFORMER CONNECTIONS.

90. Connections in Parallel (Constant=Voltage Transformers). In systems of distribution where alternating currents are delivered to a number of units (groups of lamps, for example) all at constant voltage, each unit (each group of lamps) is supplied from the secondary of a separate and distinct transformer; and the primaries of the respective transformers are connected in parallel across the constant-voltage mains that lead out from the supply alternator. This arrangement is shown in Fig. 185, in which P, P′, P″, etc., are the transformer primaries; S, S′, S″, etc., are the corresponding secondaries; and A, A′, A″, etc., are the separate receiving units or groups of lamps. For this kind of service, where the primary of a transformer is supplied at constant voltage, and it is desired that the transformer shall deliver current to a receiving unit at sensibly constant voltage irrespective of load (*i.e.*, irrespective of the number of lamps), the transformer must be designed so that a very slight decrease of induced electromotive force in the primary will permit the necessary current to flow through the primary coil. This requires that the coils of the transformer shall have as little resistance as possible, and that the primary and secondary coils shall be wound close together, so that no perceptible portion of the magnetic flux that is forced through the core by the magnetizing current may flow out of the core between the coils*, instead of passing through the secondary coil as well as through the primary coil. A transformer specially designed to realize these two conditions is sometimes called a **constant=potential transformer** or a **constant=voltage transformer.**

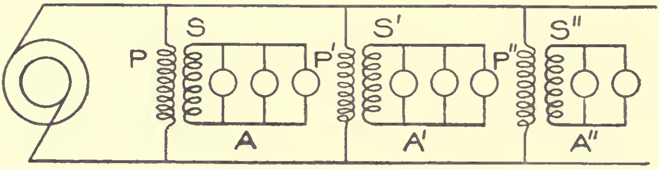

Fig. 185.

A constant-voltage transformer is necessary if it is desired to transform a given voltage in a determinate ratio′ so as to be able

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*The flow of magnetic flux *between* the two coils of a transformer is called **magnetic leakage.**

to infer the value of the given voltage from the measured value of the transformed voltage. Specially designed transformers, however, are not necessary for this purpose, for the reason that the voltmeter used for measuring the transformed voltage usually takes very little current, and it is the currents in a transformer that disturb the ideal ratio of voltage transformation.

91. Connections of Multi-Coil Transformers. Most commercial transformers are now made with two (or more) primary coils, and with two (or more) secondary coils. Each of the primary coils of such a transformer may be adapted to direct connection to 1,100-volt mains, and be wound with wire large enough to carry say 10 amperes without undue heating. In this case, if these two primary coils are properly connected in parallel they constitute in effect a single primary coil, suited to direct connection to 1,100-volt mains, and capable of taking 20 amperes without undue heating. On the other hand, if these two primary coils are properly connected in series, they constitute in effect a single primary coil suited to direct connection to 2,200-volt mains, and capable of taking 10 amperes of current without undue heating. Each of the secondary coils of such a transformer may likewise be adapted to deliver 100 amperes at 110 volts, in which case the two secondaries, if properly connected in parallel, constitute in effect a single secondary coil adapted to deliver 200 amperes at 110 volts; whereas if the two secondaries are properly connected in series, they constitute in effect a single secondary adapted to deliver 100 amperes of current at 220 volts.

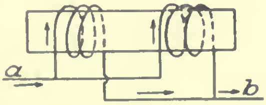


Fig. 186.

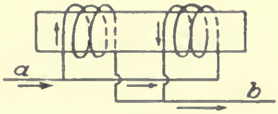


Fig. 187.

Two coils of a transformer (primary or secondary) are properly connected in parallel when the current which divides between them flows around the core in the same direction in both coils, that is, so that both coils magnetize the core in the same direction. Proper and improper connections in parallel are shown in Figs. 186 and 187.

Two coils of a transformer (primary or secondary) are properly connected in series when the current which flows through them flows around the core in the same direction in both coils. Proper and improper connections in series are shown in Figs. 188 and 189.

When two primaries of a transformer improperly connected in parallel are connected to the supply mains, the currents in the coils oppose each other in their magnetizing action on the core. The result is that the core is not preceptibly magnetized; but little opposing electromotive force is induced in the coils (by leakage flux); and the two improperly connected coils constitute a short circuit when they are connected to the supply mains.

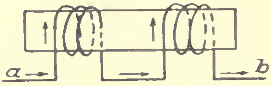


Fig. 188.

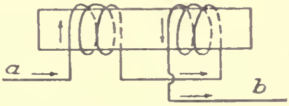


Fig. 189.

When two primaries of a transformer, improperly connected in series, are connected to the supply mains, the current which flows through the two coils will have equal and opposite magnetizing actions in the two coils. The core flux will therefore be practically zero, and no counter electromotive force will be induced in the windings to balance the applied electromotive force. The flow of current is therefore hindered only by the coil resistances, and by the electromotive forces induced by the leakage flux. The result is that two coils improperly connected in series constitute a short circuit when they are connected to the supply mains.

Two secondary coils improperly connected in parallel give rise to short-circuit conditions. Two secondary coils improperly connected in series do not lead to short-circuit conditions, but give zero electromotive force between their terminals.

92. Arrangement for Transformers for the Edison Three-Wire System. (Single-Phase.) The Edison three-wire system, extensively used in direct-current distribution, is commonly used in alternating-current distribution.

Fig. 190 shows two transformers properly connected for supplying current to a three-wire system; and Fig. 191 shows two transformers improperly connected for supplying current to a three-wire system. In the proper connection, the middle secondary main *c* carries only the difference of the currents in the outside mains *a* and *b;* and in the improper connection, the current in the middle secondary main is the sum of the currents in the outside mains. The proper connection gives double voltage between the outside secondary mains and the improper connection gives zero voltage between outside secondary mains.

The Edison three-wire system must not be confused with the two-phase and three-phase three-wire systems. The advantages of the Edison three-wire system when used for the distribution of single-phase alternating currents, are exactly the same as the advantages of this system when used for the distribution of direct currents—namely, a great saving in the copper required in the distributing mains. This saving, in general, amounts to five-eighths of the copper that would be required for a two-wire system using one-half the total voltage between outside mains. As explained in

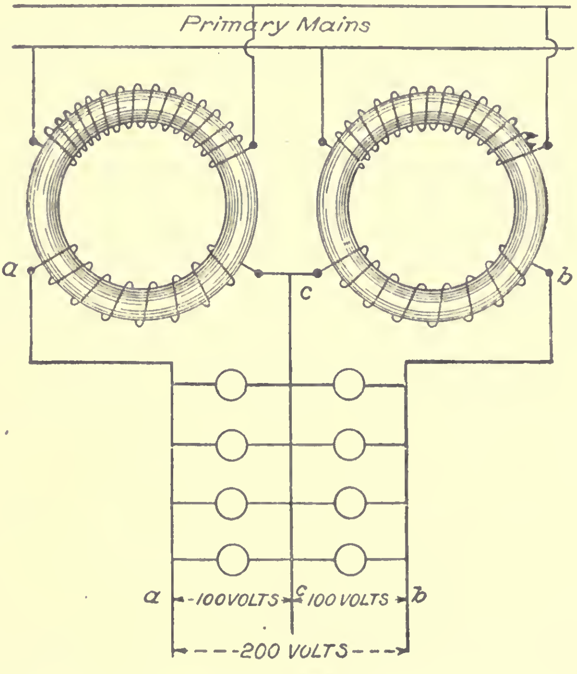


Fig. 190.

article 4 the amount of copper required varies inversely as the square of the voltage used.

Single-phase current may be supplied to Edison three-wire distributing mains by a single transformer having two secondary coils properly connected in series to the outside mains, the middle main being connected to the junction of the two secondary coils.

93. Banking of Transformers. Two service mains may be supplied with current by two or more transformers with their primaries connected in parallel between the supply mains, and with their secondaries properly connected in parallel to the service mains.

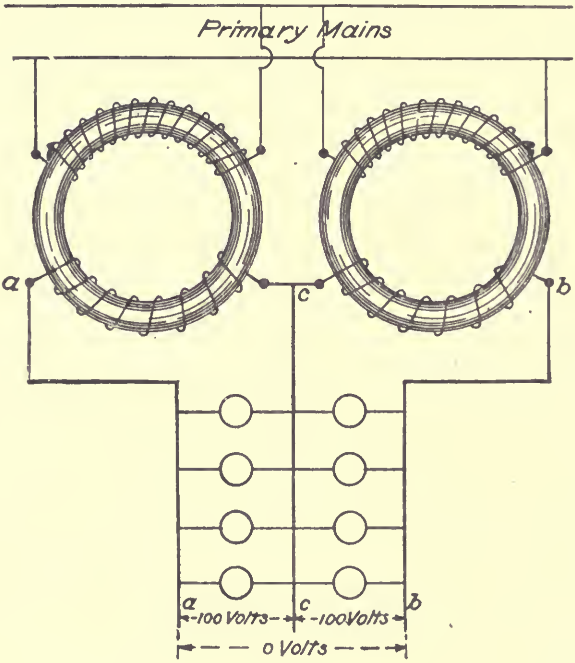


Fig. 191.

Fig. 192 shows two transformers properly "banked" so as to supply current to the two service mains *a* and *b*. In many large transmission systems, such as the Niagara-Buffalo, a dozen or more large transformers may be banked (on each phase) for step-up or step-down transformation.

94. Connections in Series (Current Transformers). In some of the older systems of distribution by alternating currents, it was desired that each receiving unit (arc lamp, for example) should receive a constant current equal to the whole, or to a definite fractional part, of the constant current delivered by an alternator. This condition can be realized by supplying each unit or group of units from the secondary of a separate and distinct transformer, the primaries of all the transformers being connected in series as shown in Fig. 193, in which P, P′, P″, P‴, etc., are the primaries of the respective transformers; S, S′, S″, S‴, etc., are the transformer secondaries; and A, A′, A″, A‴, etc., are the receiving units. For this kind of service, where the primary of a transformer is supplied with a *definite* current, and it is desired that the transformer shall deliver to a receiving unit a current which is equal to an invariable fractional part of the primary current, irrespective of variations of resistance in this unit, the transformer must be designed to take as small a magnetizing current as possible, for, according to the discussion in article 88, it is the magnetizing cur-

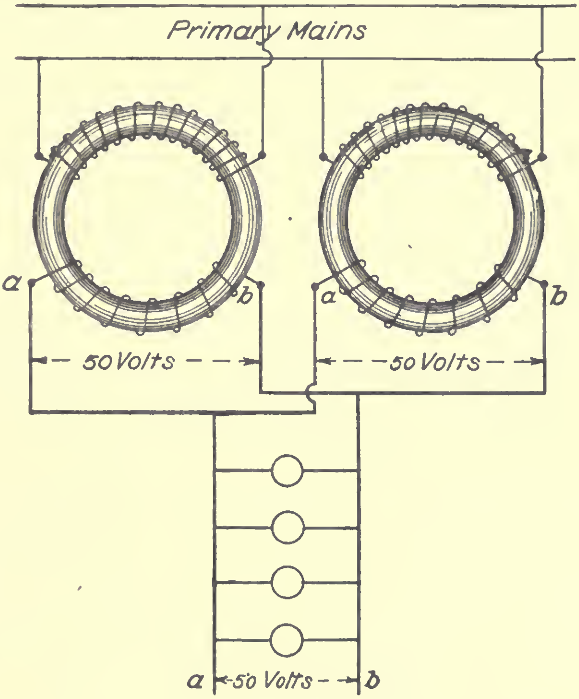


Fig. 192.

rent that disturbs the ideal relation of primary to secondary current in a transformer. A transformer which is specially designed to realize this condition is sometimes called a **current transformer.**

The transformer used in connection with the composite field excitation of an alternator, as shown in Fig. 95, is a current transformer which delivers a current equal to a definite fraction of the current output of the alternator to the rectifying commutator.

The current transformer is frequently used for sending current equal to a definite fractional part of an alternating current through an ammeter from the reading of which, together with the known ratio of current transformation, the value of the whole alternating current is deduced.

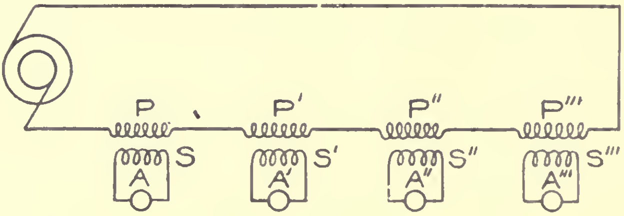


Fig. 193.

The current transformer here described must not be confused with the so-called **constant-current transformer** described in article 108*d*, which receives variable current from a constant voltage supply, and delivers a constant current to a group of receiving units connected in series, the delivered current being constant irrespective of increase or decrease in the number of receiving units.

The connection of a transformer primary in series in a circuit containing many other elements (lamps) so that the current passing through the primary does not vary much with the varying resistance of the circuit to which the secondary of the transformer delivers current, gives rise to actions which are not very familiar to electrical engineers, for the reason that this arrangement is now seldom used in practice. The actions, however, are interesting. They are as follows:

Fig. 194 represents a transformer primary P connected in series in a circuit containing many elements e', e'', e''', e^{IV}, etc. (lamps). The action will be described in two steps—namely, (*a*) on the assumption that the magnetizing current of the transformer is always negligible, and (*b*) without the aid of this simplifying assumption.

(*a*) If the magnetizing current is always negligibly small, then the current in A is equal to a fixed fractional part of the sensibly constant current in the main circuit, so that any increase of the resistance or reactance of A must be accompanied by a corresponding increase of the voltage E″, which is pushing current through A; and this must be accompanied by a corresponding increase of the voltage E′ between the terminals of the primary coil P. Thus, if A has zero resistance and zero reactance then E″ is zero, and E′ is zero. That is, the current in the main circuit flows through P without any opposition at all, just as if P were a connection of zero resistance.

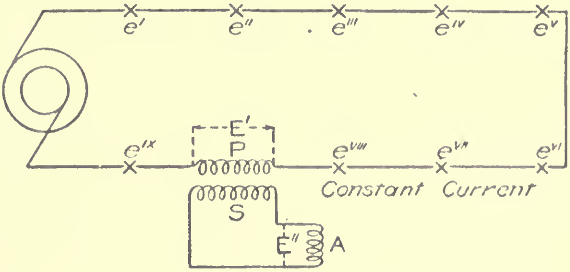


Fig. 194.

If the resistance or reactance of A is increased, E″ (and also E′) must increase, which means that the current in the main circuit encounters greater and greater opposition in flowing through P.

If the circuit of A is opened (infinite resistance), then, on the above assumption of negligible magnetizing current, the opposition to the flow of current in P becomes infinite, so that breaking the circuit of A is equivalent to breaking the main circuit.

(*b*) As a matter of fact, as the resistance or reactance of A is increased, causing an increase of E″ and E′, the magnetism of the transformer core must increase proportionally with E″ and E′ in order that these increased voltages may actually be induced in the transformer coils; and this increase of magnetism of the core requires more and more magnetizing current. (It must be remembered that the magnetizing current is that part of the primary current whose magnetizing action is not balanced or annulled by the secondary current as explained in article 88.) The magnetizing current, therefore, is not, always negligible irrespective of the resistance of A. In fact, when the resistance of A is infinite (open circuit), there is no secondary current; all the current in the coil P is magnetizing current; and the voltage E′, which opposes the flow of current through P, rises only to that value which corresponds to the degree of magnetism of the core that can be produced by the magnetizing action of the whole primary current. The transformer then becomes simply a choke coil.

95. The Auto-Transformer. Given a source of supply of alternating current: This current may be delivered to a receiving unit in three ways:

(*a*) By connecting the unit directly to the supply mains.

(*b*) By connecting the unit to the secondary of a transformer of which the primary is connected to the supply mains.

(*c*) By a combination of methods *a* and *b*.

The combination method may be realized with any ordinary transformer; and when an ordinary transformer is so used, it is called an **auto-transformer.**

It will appear in the following discussion that when the voltage of the supply differs but little from the desired service voltage, the combination method is much preferable to the method in which the transformer alone is used, because of the fact that a smaller transformer suffices, and because the combination method involves less energy loss. This combination or auto-transformer method is quite simple of treatment when attention is confined to a particular case; but it is complicated when attempt is made to give it a general discussion, that is, when attempt is made to discuss all the theoretically possible ways in which a given ordinary transformer may be used as an auto-transformer.

In Fig. 195 A and B are alternating-current supply mains, between which the voltage is say 100; C and D are service mains, to which it is desired to deliver alternating current at 90 or 110 volts; P and S are the primary and secondary coils of an ordinary transformer. The primary P is connected to A and B as shown. The secondary S has one-tenth as many turns as P, therefore the voltage induced in S is one-tenth of the voltage acting on P, or 10 volts. Let the dotted arrows represent the directions of the induced electromotive forces in the two coils at a given instant. Then the long heavy arrow will represent the direction of the voltage between the mains at the same instant, inasmuch as the induced voltage in the primary coil of a transformer is always opposed to the supply voltage.

(*a*) *Auto-Step-up Transformation.* The 10 volts induced in the coils, Fig. 195, will help push current into the service mains if we connect from supply main A, out of which the current at the given instant is tending to flow, to terminal *g* of coil S, connect from terminal *f* to service main C, and connect from service main D to supply main B, as shown by the dotted lines. In this case, the voltage induced in the coil S is added to the supply voltage, and the service voltage is therefore 110 volts.

(*b*) *Auto-Step-down Transformation.* The ten volts induced in the coil S will oppose the flow of current into the service mains if we connect from supply main A to terminal *f*, connect from terminal *g* to service main C, and connect from service main D to supply main B, as shown by the dotted lines in Fig. 196. In this case the induced voltage in the coil S is subtracted from the supply voltage, and the service voltage is now 90.

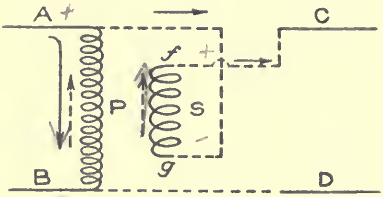


Fig. 195.

Current Relations in the Auto-Transformer. In Figs. 195 and 196 the directions of the induced voltages in P and S are shown by the dotted arrows. These induced voltages are in the same direction in the two coils. The currents in the two coils of a transformer are, on the other hand, always in opposite directions, inasmuch as they balance each other's magnetizing action. Suppose for the sake of concreteness that ten amperes are delivered to the service mains. Then we have the following relations:

(*a*) Ten amperes flow through S, Fig. 195, *in the same direction* as the induced electromotive force of ten volts, so that one ampere (one-tenth as much current, since there are ten times as many turns in P as in S) flows through P in *opposition* to the induced or counter electromotive force of 100 volts. Therefore the coil P takes 100 watts from the supply mains, which power is transferred to the coil S by ordinary transformer action whence it is given out (ten volts pushing ten amperes) in assisting the flow of current to the service mains. The total power delivered to CD is evidently 1,100 watts (10 amperes at 110 volts), and of course the total power taken from the supply mains is 1,100 watts (11 amperes at 100 volts).

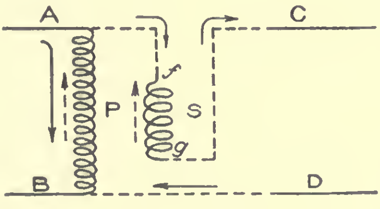


Fig. 196.

(*b*) Ten amperes flow through S, Fig. 196, in a direction *opposite* to the ten volts of induced electromotive force, so that one ampere flows through P in the same direction as the induced electromotive force of 100 volts. Therefore, of the 1,000 watts delivered by the supply mains in forcing the ten amperes through S and through the service mains, 100 watts are delivered to the coil S, and 900 watts are delivered to the service mains (10 amperes at 90 volts). The 100 watts delivered to S are transferred by transformer action to the coil P, and delivered by P back to the supply mains.

It is to be particularly noted that only 100 watts are involved in the above as genuine transformer action, although 900 or 1,000 watts are actually delivered to the service mains.

96. Use of Transformers in Polyphase Systems. A polyphase transmission system is essentially the utilization of two or three entirely separate and distinct single-phase transmission systems of which the separate and distinct electromotive forces or currents are maintained in definite phase relations with each other by mechanical connections in the generator. Step-up or step-down transformation in a polyphase system is accomplished, in general, by a separate and distinct transformer of the ordinary type for each phase.

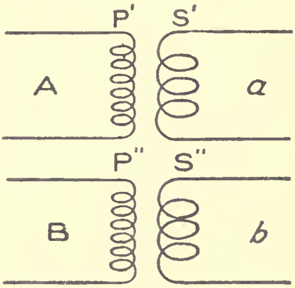


Fig. 197.

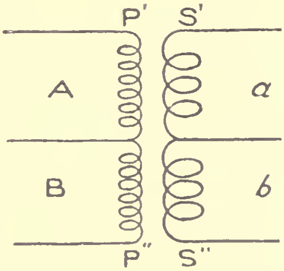
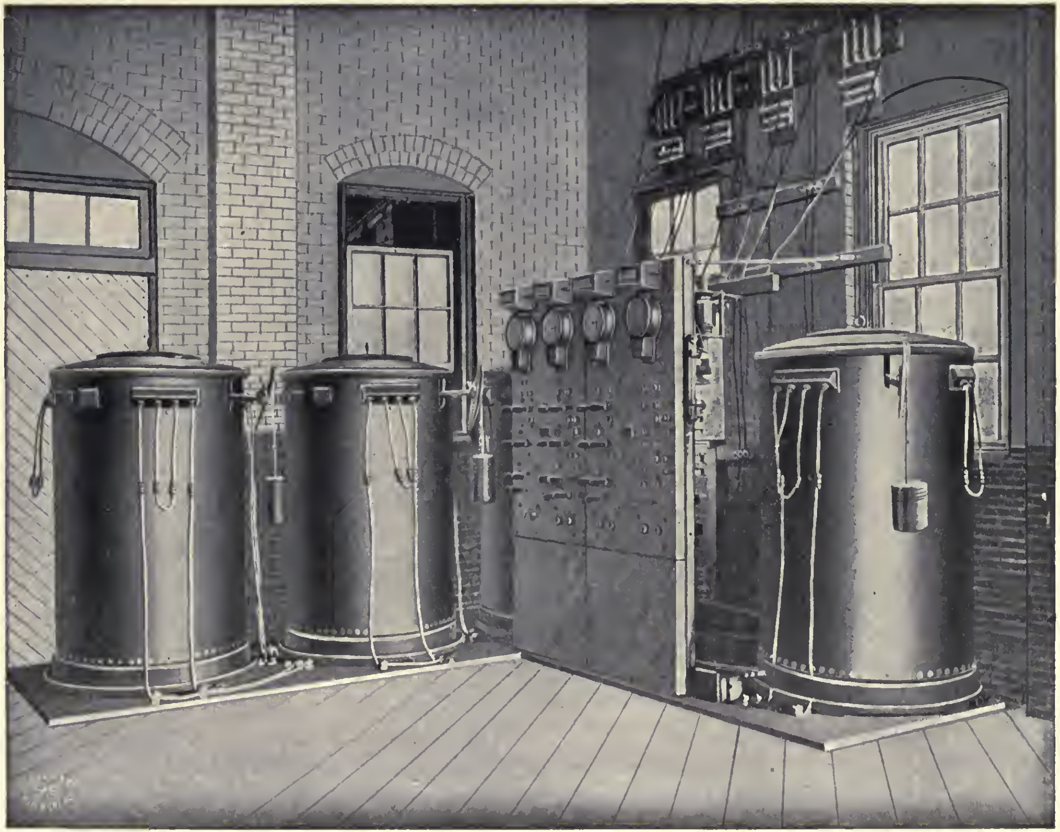


Fig. 198.

97. Transformers on a Two-Phase System. Fig. 197 shows a two-phase system in which the current of each phase A and B is transmitted over an entirely independent circuit, and the electromotive force of each phase is stepped down (or up) by an ordinary transformer P'S' and P''S'' respectively. Fig. 198 shows what is called the *three-wire, two-phase system*, in which one line wire is used as a common return wire for both phases, and where two ordinary transformers P'S' and P''S'' are used for stepping the voltage down (or up). These two figures contain all that is essential in the step-down or step-up transformation of a two-phase system.

98. Transformers on a Three-Phase System. The usual transmission line for a three-phase system consists of three wires.



INSTALLATION OF CONSTANT-CURRENT TRANSFORMERS.

General Electric Co.

each wire being in effect a common return for currents that pass out over the other two. In this case, the usual arrangement for step-down (or step-up) transformation is to connect the three primaries of three ordinary transformers to the supply mains, using either Y or Δ connections; and to connect the three secondaries to the service mains, using either Y or Δ connections. Furthermore, the primaries may be Y-connected and the secondaries Δ-connected, or *vice-versa.* The Δ connections of both primaries and secondaries is preferred in practice, inasmuch as with this arrangement the complete three-phase step-down (or step-up) transformation is still effected even though one transformer may

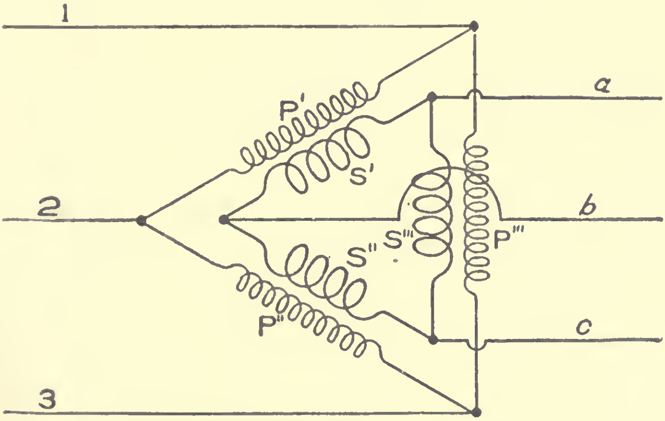


Fig. 199.

be entirely disconnected because of burn-out or break-down. In such a case, however, the two remaining transformers do not have two-thirds of the transforming capacity of all three, but only $\frac{85}{100}$ of $\frac{2}{3} = 0.567$ as much, or a little over one-half the capacity.

Fig. 199 shows three ordinary transformers P′S′, P″S″, and P‴S‴, with their primaries Δ-connected to three-wire, three-phase supply mains 1, 2, and 3; and with their secondaries Δ-connected to three-wire three-phase service mains *a*, *b*, and *c*.

Fig. 200 shows the arrangement of Fig. 199 with one of the transformers P‴S‴ omitted (any one of the three may be omitted). This arrangement (Fig. 200) is operative for three-phase, three-wire step-up or step-down transformation, except that its power capacity is only about 57 per cent of the power capacity of the arrangement in which three similar transformers are used.

99. Polyphase Transformers with Compound Magnetic Circuits. Let A and B, Fig. 201, be the two separate transformers to be used for step-up or step-down transformation on a two-phase system. Each iron core may have its own return circuit for the magnetic flux; or a single magnetic return C may be used for the two as shown in Fig. 202. In the latter case only 1.4 as much iron need be used for the common return as would have to be used for each single magnetic return.

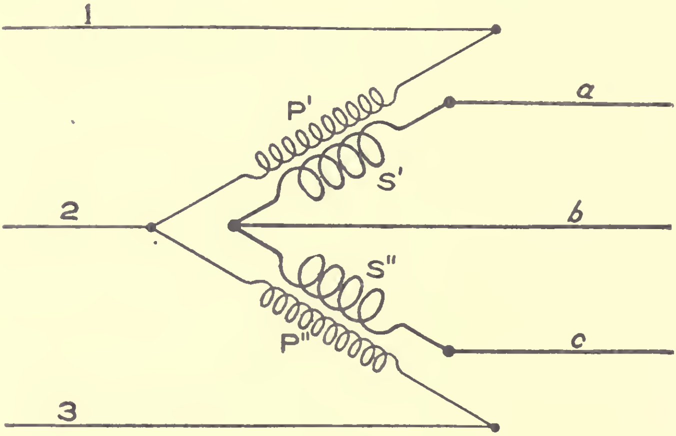


Fig. 200.

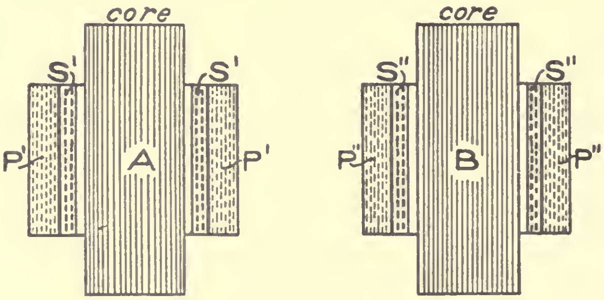


Fig. 201.

Similarly, three transformers A, B, and C, Fig. 203, used for step-up or step-down transformation on a three-phase system, may be combined magnetically so that each transformer core is the magnetic return for the other two, as shown.

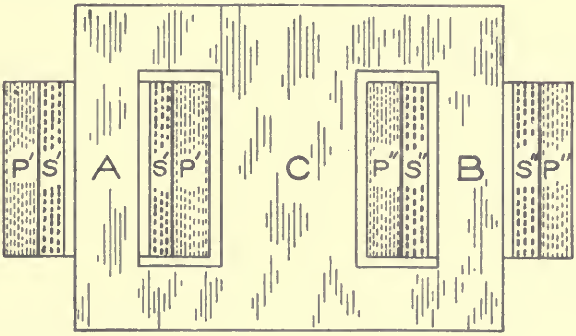


Fig. 202.

TRANSFORMATION OF TWO-PHASE TO THREE-PHASE CURRENTS, AND VICE VERSA.

100. Phase Transformation. Given a two-phase* supply connected to the similar primaries of two transformers. Then *an electromotive force of any desired value and of any desired phase may be produced*, as follows:

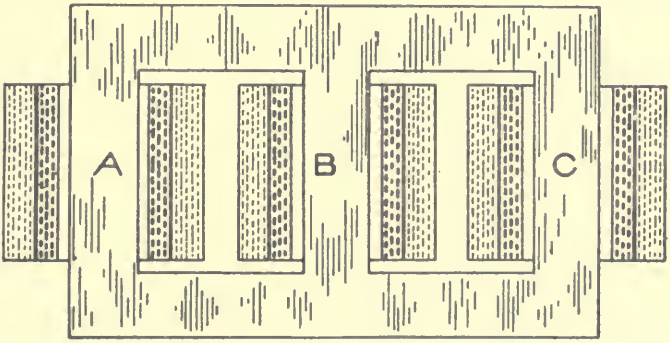


Fig. 203.

Fig. 204 shows the two-phase supply mains connected to the similar primaries P′ and P″ of two separate transformers. On core A is wound a secondary coil *a*, and on core B is wound a secondary coil *b*; these two secondary coils are connected in series, and the desired electromotive force E is produced by the two secondary coils in conjunction. In order that the desired electromotive force E may be produced by coils *a* and *b* jointly, the following conditions must be fulfilled:

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*Or three-phase supply. The discussion of phase transformation is, however, much simpler with a two-phase supply.

Let the vectors A and B in the clock diagram, Fig. 205, represent the two two-phase electromotive forces; and let E represent the desired electromotive force. *Then coil a (Fig. 204) must be wound with a sufficient number of turns of wire to produce the component a* of E; *and coil b must be wound with a sufficient number of turns of wire to produce the component b* of E. See Fig. 205.

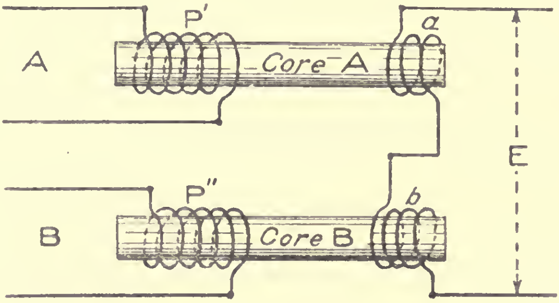


Fig. 204.

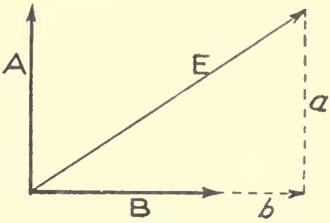


Fig. 205.

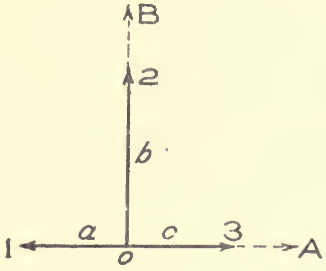


Fig. 206.

The general two-phase, three-phase transformer consists of two separate iron cores wound with similar primary coils P′ and P″, which are connected to the respective phases of the two-phase system, as shown in Fig. 204; *and each of the three-phase electromotive forces is produced by a pair of secondary coils, one on* *each core.* Each of these *pairs* of coils we shall call a *unit.* These three units, in general, may be either Y-connected or Δ-connected to three-wire three-phase service mains.

The general two-phase, three-phase transformer is greatly simplified if we choose to have *one of the three-phase electromotive forces in phase with one of the two-phase electromotive forces.* Thus, if E, Fig. 205, is in phase with B, then E may be produced by a single secondary coil on core B, instead of being produced by a pair of secondary coils, one on each core.

101. The Scott Transformer. The two-phase, three-phase transformer permits of still further simplification if the Δ connection of the three-phase units is excluded, that is, if the three-phase units are to be adapted only for Y-connection to the three-phase mains. This ultimate simplification is realized in the Scott transformer.

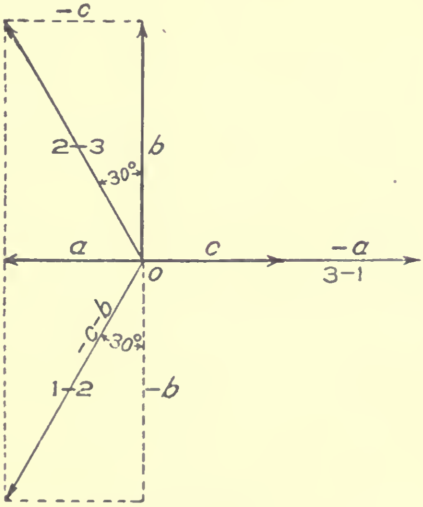


Fig. 207.

In this transformer three secondary coils only are used, one on core B, Fig. 204, giving the electromotive force *b*, Fig. 206, and two similar coils *a* and *c* on core A, Fig. 204, giving the electromotive forces *a* and *c*, Fig. 206. The points 1, 2, and 3, Fig. 206, are at the angles of an equilateral triangle. One terminal of each coil *a*, *b*, and *c* is brought to a common connection represented by the point 0, Fig. 206; and the other terminal of each coil is connected to one of the three-phase mains. The points 1, 2, and 3, Fig. 206, represent the three-phase mains. Now, from an inspection of Fig. 206, it is evident that the electromotive force *a* helps to push current in a receiving circuit from main 1 to main 2; while electromotive force *b* opposes *a* in this respect. Therefore the electromotive force from main 1 to main 2 is $a - b$, as shown in Fig. 207. Similarly the electromotive force

b helps to push current in a receiving circuit from main 2 to main 3, while electromotive force c opposes b in this respect. Therefore the electromotive force from main 2 to main 3 is $b - c$, as shown in Fig. 207. Lastly the electromotive force c helps to push current in a receiving circuit from main 3 to main 1, while the electromotive force a opposes c in this respect. Therefore the electromotive force from main 3 to main 1 is $c - a$, as shown in Fig. 207.

This discussion shows that the electromotive forces between mains 1 to 2, 2 to 3, and 3 to 1 have the common value E volts, and are 120° apart in phase, provided

$$b = E \cos 30^\circ.$$

and

$$a = c = E \sin 30^\circ.$$

From the clock diagram, Fig. 207, it is evident that the common junction of the two coils a and c is a point *towards* which the electromotive force in one coil is pushing, and *from* which the electromotive force in the other coil is pushing at the same instant. Therefore the common junction of these two coils may be thought of as the *middle point* of one continuously wound secondary coil on core A, as shown in Fig. 208.

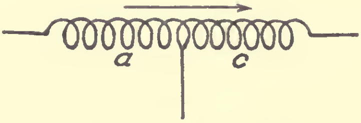


Fig. 208.

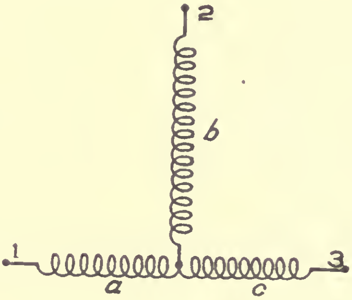


Fig. 209.

A clear idea of the Scott transformer may now be obtained as follows: Two similar cores have similar primary coils, which are connected to the respective phases of a two-phase system. One of these cores has a secondary winding b, Fig. 209, one end of which is connected to one of the three-phase mains (main 2, as shown in Fig. 209), and the other end of which is connected to the middle point of the secondary winding $a\,c$, which is wound on the other core. The terminals of the winding $a\,c$ are connected to the remaining two of the three-phase mains (mains 1 and 3, as shown in Fig. 209). The entire secondary winding *ac* has $\frac{2}{\sqrt{3}}$ times as many turns of wire as the coil *b*; that is, 1.16 times as many turns.

The complete connections of the Scott transformer are shown in Fig. 210.

The three-phase system requires less line copper than either the single-phase or the two-phase systems to transmit a given amount of power with a given line voltage and with a given loss. Hence, for the long-distance transmission of electric power, the three-phase system is universally adopted in this country. For the local distribution of electric power, on the other hand, the two-phase system offers certain advantages. It is often the case, therefore, that two-phase alternators are used to generate alternating currents at a central station, and that two-phase currents are used for power and lighting purposes in the neighborhood of the station. When, however, power is to be transmitted to points fifteen or more miles distant, it becomes desirable, as explained above, to use the three-phase system. It is in such cases, especially, that phase transformation is used. The Niagara-Buffalo transmission is the best as well as the most extensive example of this practice. Power is generated by eleven 5,000-horse-power, two-phase alternators at 2,200 volts. A large part of this power is distributed to factories and chemical works in the vicinity of the central power plant. A large amount of power is transmitted to Buffalo, a distance of eighteen miles, by means of three-phase alternating currents derived from the two-phase alternators by two-phase, three-phase transformation. Scott transformers are used; and the two-phase currents at a voltage of 2,200 are stepped up to 22,000 volts, and at the same time are transformed to three-phase currents. At Buffalo, the three-phase, high-voltage currents are stepped down to about 2,200 volts, and are transformed back into two-phase currents, also by Scott three-

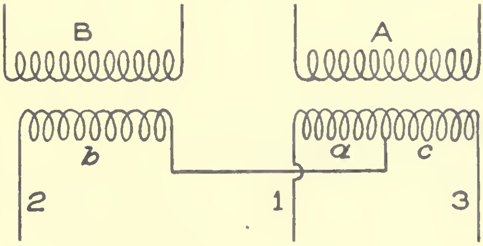


Fig. 210.

phase, two-phase transformers. The 2,200-volt two-phase currents are then distributed by feeders and service mains for lighting and power purposes throughout the city.

102. Transformer Losses. The power output of a transformer is less than its power intake because of the losses in the transformer. These losses are: (*a*) The iron or core losses due to eddy currents and hysteresis; and (*b*) the copper losses due to the resistances of the primary and secondary coils.

(*a*) The **iron losses** are practically the same in amount at all loads. They depend upon the frequency and range of the flux density $\mathcal{B}$, upon the quality and volume of the iron, and upon the thickness of the laminations.

The hysteresis loss, in watts, is:

$$W_h = \eta V f \mathcal{B}^{1.6}, \qquad (34)$$

in which f is the frequency in cycles per second; $\mathcal{B}$ is the maximum flux density in the iron core, in lines per square centimeter; V is the volume of the iron, in cubic centimeters; and η is a constant depending upon the magnetic quality of the iron. For annealed refined sheet iron the value of η is about 2×10^{-10}.

TABLE IV.

Transformer Efficiencies, Losses, Etc.

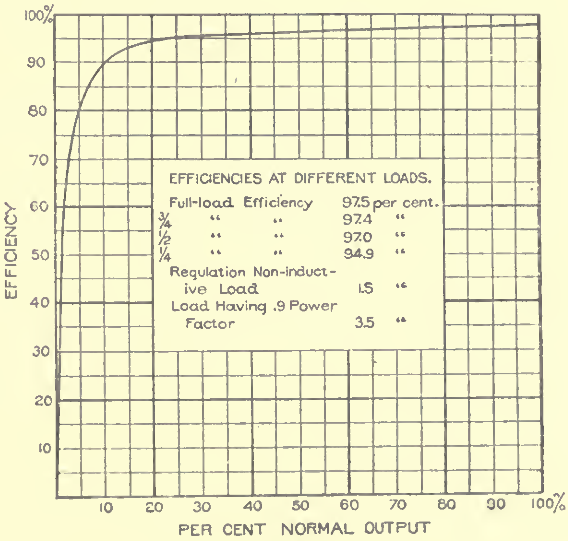
K.W.	Core Loss	Copper Loss	Regulation	EFFICIENCIES				Weight, in Lbs.
				Full Load	¾ Load	½ Load	¼ Load	
.6	23	16	2.68	93.9	93.4	91.7	86.2	65
1.0	30	27	2.72	94.6	94.3	93.1	88.7	75
1.5	35	36	2.47	95.5	95.3	94.5	90.0	95
2.0	43	45	2.42	95.8	95.7	94.9	91.6	125
2.5	45	56	2.26	96.1	96.1	95.5	92.7	160
3.0	48	64	2.15	96.4	96.4	95.9	93.5	200
4.0	60	87	2.21	96.4	96.5	96.1	93.9	225
5.0	64	103	2.14	96.8	96.8	96.5	94.7	270
7.5	96	146	1.99	96.9	96.9	96.6	94.7	470
10.0	114	176	1.79	97.2	97.2	96.9	95.2	535
15.0	150	250	1.74	97.4	97.5	97.2	95.7	700
20.0	180	322	1.65	97.5	97.6	97.5	96.2	875
25.0	200	385	1.50	97.7	97.8	97.7	96.5	1,050
30.0	230	445	1.50	97.8	97.9	97.8	96.7	1,275
40.0	275	550	1.44	98.0	98.1	98.0	97.0	1,400
50.0	330	660	1.34	98.1	98.2	98.1	97.1	1,600

The eddy current loss, in watts, is:

$$W_e = bVf^2l^2\mathcal{B}^2. \qquad \textbf{(35)}$$

in which l is the thickness of the laminations, in centimeters; and b is a constant depending upon the specific electrical resistance of the iron. For ordinary iron the value of b is about 2.5×10^{-11}. Insufficient insulation of laminations causes excessive eddy current loss.

Equations 34 and 35 may be used for calculating the hysteresis and eddy-current losses in any mass of laminated iron subjected to periodic magnetization, such as alternator armatures, and the rotor and stator iron in an induction motor.



EFFICIENCIES AT DIFFERENT LOADS.

Full-load Efficiency	97.5 per cent.
¾ " "	97.4 "
½ " "	97.0 "
¼ " "	94.9 "
Regulation Non-inductive Load	1.5 "
Load Having .9 Power Factor	3.5 "

Fig. 211.

(*b*) The **copper loss**, in watts, is:

$$W_c = R'I'^2 + R''I''^2. \qquad \textbf{(36)}$$

This loss is nearly zero when the transformer is not loaded; it increases with the square of the current; and becomes excessive when the transformer is greatly overloaded.

103. Transformer Efficiency. The ratio *power output* : *power intake* is called the *efficiency* of a transformer.

Table IV, on page 230, shows the efficiencies, losses, etc., of a series of transformers designed and manufactured by a large American company. These transformers are designed for a frequency of 60 cycles per second, and a primary voltage of 1,040 or 2,080 volts, according to whether the two halves of the primary coil are connected in parallel or in series.

Fig. 211 shows graphically the relation between the efficiency and the per cent of normal output for a 150-K.W. Westinghouse transformer designed for 15,000 volts secondary, 500 volts primary (step-up), and a frequency of 60 cycles per second (7,200 alternations per minute).

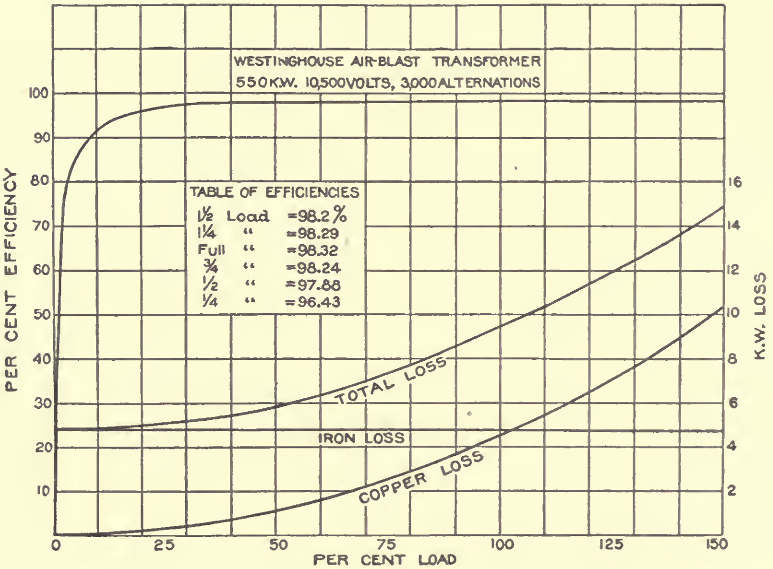


TABLE OF EFFICIENCIES

1½	Load	=98.2 %
1¼	"	=98.29
Full	"	=98.32
¾	"	=98.24
½	"	=97.88
¼	"	=96.43

Fig. 212.

Fig. 212 shows graphically the various losses and the efficiency of a Westinghouse air-blast transformer rated at 550 kilowatts used to step up from 500 volts to 10,500 volts at a frequency of 25 cycles per second (3,000 alternations per minute).

In Fig. 212, the curve representing the iron loss is plotted as a horizontal straight line because the iron loss for a given transformer is constant for all loads. The curve representing the copper loss is a parabola. The efficiency of a given transformer is a maximum at that load for which the iron loss is equal to the copper loss. This load is evidently the abscissa of the point at which the iron-loss line intersects the copper-loss curve. As seen in Fig. 212, the maximum efficiency occurs at about 101 per cent of full load, and at any other load (for the given transformer) the efficiency will be less than at 101 per cent of full load.

Calculation of Efficiency. The transformer output (non-inductive receiving circuit) is E″I″. The internal loss is $W_h + W_e + W_c$, so that the intake is $E''I'' + W_h + W_e + W_c$, and the efficiency is:

$$\text{Efficiency} = \frac{E''I''}{E''I'' + W_h + W_e + W_c}. \qquad \textbf{(37)}$$

All-day Efficiency. Usually a transformer is connected to the mains continuously, and current is taken from the secondary for a few hours only, each day. In this case the iron loss is incessant and the copper loss is intermittent. The total work given to the transformer during the day may greatly exceed the total work given out by it, especially if the incessant iron losses are not reduced to as low a value as possible. The ratio *total work given out by the transformer ÷ total work received by the transformer during the day* is called the "all-day efficiency of the transformer. In other words, it is the ratio $\frac{\text{total watt-hours output}}{\text{total watt-hours input}}$ during the day. The all-day efficiency is given by the formula:

$$\text{all-day efficiency} = \frac{E''I'' \times t}{E''I'' \times t + (W_h + W_e) \times 24 + W_c \times t} \qquad \textbf{(38)}$$

in which t is the number of hours during the day of 24 hours that the transformer is loaded, and I″ is the average current delivered by the secondary while the transformer is loaded. The other symbols have the same significance as in article 102.

Since the iron loss of a given transformer is incessant as long as the transformer is connected to the primary supply mains, it follows that to obtain a high all-day efficiency, it is necessary to use a transformer whose iron loss is as small as possible. In general, if a transformer is to be operated at light loads the greater part of the day, it is much more economical to use a transformer designed for a small iron loss than for a small full-load copper loss.

Transformers are usually designed so that at full load the copper loss is approximately equal to the iron loss.

104. Transformer Regulation. The secondary terminal voltage of a transformer falls off in value with increasing load, and rises with decreasing load. The rise of secondary terminal voltage from full load to zero load (at constant primary applied voltage), expressed in per cent of the full load secondary voltage, is called the *regulation* of a transformer.

Example. A certain 5-K.W. transformer gave a secondary terminal voltage of 200 volts at full load; when the load was reduced to zero, the voltage rose to 205 volts. In accordance with the above definition, the regulation of this transformer is:

$$\frac{(205 - 200)}{200} \times 100 = 2.5 \text{ per cent.}$$

The regulation of a transformer is smaller when used for supplying a non-inductive load (such as incandescent lamps), than when supplying an inductive load (such as induction motors). The regulation of a series of transformers is given in Table IV, page 230.

105. Practical and Ultimate Limits of Output of a Transformer. When the secondary current of a transformer is increased, the secondary electromotive force drops off, and the power output increases with the current, reaching a maximum as in the case of the alternator. This maximum power output is the ultimate limit of output of the transformer. Practically, the output of a transformer is limited to a much smaller value than this maximum output, (*a*) because of the necessity of cool running; (*b*) because in most cases it is necessary that the secondary electromotive force be nearly constant; and (*c*) because the efficiency of a transformer is low at excessive outputs.

Small transformers have relatively large radiating surfaces; and in such transformers the requirements of a small regulation, as a rule, determine the allowable output.

Large transformers, on the other hand, have relatively small radiating surfaces, and their allowable output is limited by the permissible rise in temperature. Very large transformers are usually provided with air passages through which air is made to circulate by a fan. Sometimes transformers are submerged in oil, which, by convection, carries heat from the transformer to its enclosing case, where it is radiated.

106. Rating of Transformers. A transformer is rated according to the power it can deliver continuously to a non-inductive receiving circuit without undue heating; and the ratio of transformation, together with a specification of the frequency and effective value of the primary electromotive force to which the transformer is adapted, are also given by the manufacturer.

In order to secure uniformity in the rating of transformers by manufacturers, the American Institute of Electrical Engineers recommends the following rules concerning the allowable rise of temperature:

> In transformers for continuous service, a rise of temperature of copper not exceeding 50° C (as measured by change of electrical resistance of primary and secondary coils), and a rise of temperature of other parts not exceeding 40° C, (as measured by a thermometer laid against the part, the core for example), under normal conditions as to ventilation.
>
> In the case of transformers intended for intermittent service, or not operating continuously at full load, but continuously in circuit, as in the ordinary case of lighting transformers, the temperature elevation above the surrounding air temperature should not exceed 50° C as measured by resistance in electric circuits, and 40° C as measured by the thermometer in other parts, after the period corresponding to the term of full load. In this instance, the test load should not be applied until the transformer has been in circuit for a sufficient time to attain the temperature elevation due to core loss. With transformers for commercial lighting, the duration of the full-load test may be taken as three hours, unless otherwise specified.

The **over-load rating** of a transformer is recommended to be 25 per cent for two hours; and it is based upon an allowable increase of temperature of 15° C above that specified for full load, as given above. This extra rise of temperature is to be measured after the transformer has been operating for two hours on 25 per cent over-load, the transformer having previously acquired the temperature corresponding to full-load continuous operation.

When, however, transformers are to be used with other apparatus for which an over-load capacity in excess of 25 per cent is guaranteed, the same guarantee should apply to the transformers.

Abnormal Conditions of Operation. Transformers are frequently used under conditions departing more or less widely from the conditions specified by the manufacturer in regard to values of primary and secondary voltages, frequency, and current output. Thus, if a transformer is used with a primary applied voltage in excess of the rated value (frequency being unchanged), the core flux will be increased according to equation 33, and the core losses will be increased according to equations 34 and 35.

If, on the other hand, a transformer is used with a frequency less than the rated frequency (the voltage applied to the primary being unchanged), the core flux will be increased according to equation 33, and the hysteresis loss in the core will be increased according to equation 34; whereas the eddy current loss is unchanged.

It is evident from the above statements that the core loss in a given transformer may be kept at a constant value by making a simultaneous increase of both applied primary voltage and frequency.

The increase of core loss due to increase of primary applied voltage, or to decrease of frequency, or to both, may be compensated for by reducing the allowable current output, and thereby reducing the copper loss, in order that the total heating of the transformer may not exceed the normal amount.

Examples. A given transformer is rated at 5 kilowatts, and is designed to take current from 1,100-volt mains at a frequency of 60 cycles per second. Under these conditions hysteresis loss W_h, eddy current loss W_e, and copper loss W_c, will be called normal.

(*a*) The transformer is loaded so that the output is 6 kilowatts at the rated electromotive force and frequency. Find W_c in terms of normal.

(*b*) The transformer is used at rated electromotive force, but at a frequency of 75 cycles per second. Find W_h and W_e each in terms of normal.

(*c*) The transformer is used at rated frequency, but with primary electromotive force of 1,500 volts. Find W_h and W_e each in terms of normal.

(*d*) The transformer is used on primary electromotive force of 1,500 volts. Find f for which W_h is normal.

(*e*) With primary electromotive force of 1,500 volts, what load would give normal W_c?

Solution.—(*a*) Increasing the output in the ratio 5 to 6, increases both primary current and secondary current in the same ratio, and therefore increases $R'I'^2$ and $R''I''^2$ in the ratio of 5^2 to 6^2. Therefore the total copper loss become $\frac{36}{25} = 1.44$ times the normal copper loss.

(*b*) Increasing the frequency in the ratio 60 to 75 decreases the flux-density $\mathscr{B}$ in the same ratio, namely, 75 to 60. Hence the hysteresis loss is decreased in the ratio $75^{.6}$ to $60^{.6}$, or $\left(\frac{60}{75}\right)^{.6}$, or 0.87. Therefore the hysteresis loss at the increased frequency is 0.87 times the normal hysteresis loss.

From equation 35, the eddy current loss is proportioned to $f^2\mathscr{B}^2$. In the case under consideration, f is increased and $\mathscr{B}$ is decreased in the same ratio, so that the product $f^2\mathscr{B}^2$ remains unchanged. Hence the eddy-current loss in a given transformer is independent of the frequency with given primary applied voltage.

(*c*) Increasing the primary voltage in the ratio 11 to 15 increases the flux-density $\mathscr{B}$ in the same ratio. Therefore the hysteresis loss is increased in the ratio $\left(\frac{15}{11}\right)^{1.6} = 1.64$; and the eddy current loss is increased in the ratio $\left(\frac{15}{11}\right)^{2} = 1.86$. That is, the hysteresis loss becomes 1.64 times its normal value; and the eddy current loss becomes 1.86 times its normal value.

(*d*) The hysteresis loss is proportional to $f\,\mathscr{B}^{1.6}$; and $\mathscr{B}$ is proportional to $\frac{E'}{f}$; therefore, the hysteresis loss is proportional to $f \times \left(\frac{E'}{f}\right)^{1.6}$ or to $\frac{E'^{1.6}}{f^{0.6}}$. This ratio $\frac{E'^{1.6}}{f^{0.6}}$ must have the same value under the normal conditions as under the new conditions, if the hysteresis loss is to be the same. That is:

$$\frac{(1{,}100)^{1.6}}{(60)^{0.6}} = \frac{(1{,}500)^{1.6}}{x^{0.6}};$$

$$\text{or } (1{,}100)^{1.6} \times x^{0.6} = (60)^{0.6} \times (1{,}500)^{1.6};$$

or taking logarithms of both sides, we have:

$1.6 \times \log 1{,}100 + 0.6 \times \log x = 0.6 \times \log 60 + 1.6 \times \log 1{,}500$; or, $0.6 \times \log x = 0.6 \times \log 60 + 1.6 \times \log 1{,}500 - 1.6$

× log 1,100; from which we find n equal to 137 cycles per second.

(*e*) The copper loss W_c has normal value when the primary and secondary currents have normal value. Therefore, when the primary applied voltage is increased in the ratio 11 to 15, the output increases in the same ratio, the current and W_c being

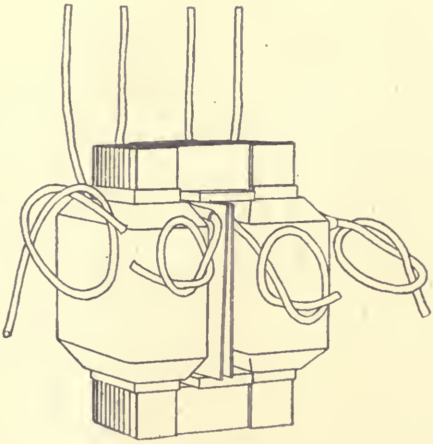


Fig. 213.

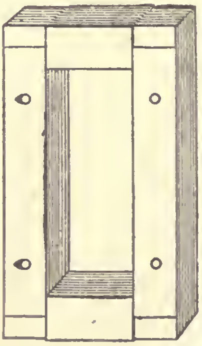


Fig. 214.

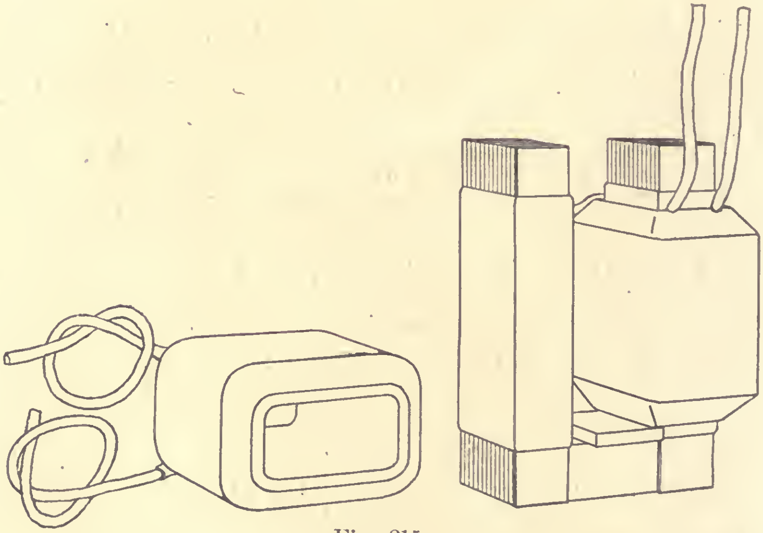
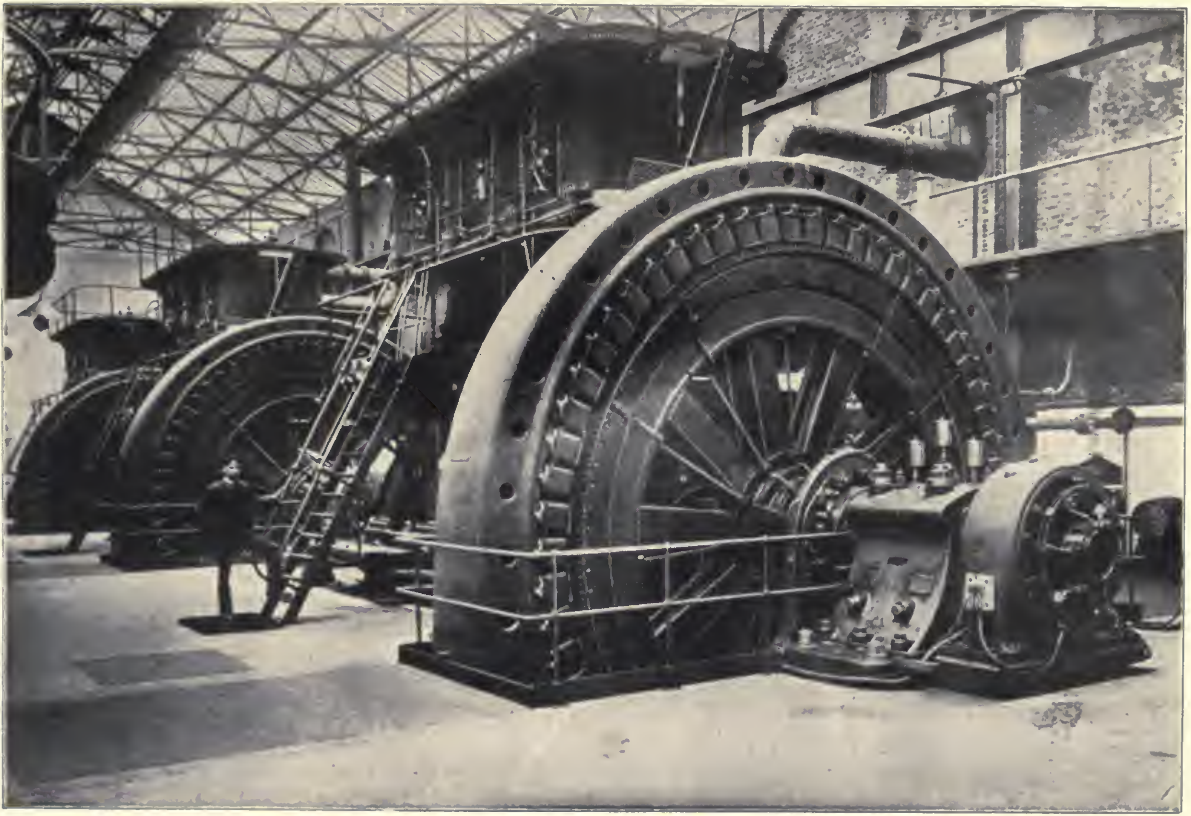


Fig. 215.



WESTINGHOUSE TWO-PHASE GENERATORS, DIRECT-CONNECTED.

Metropolitan Electric Supply Co., Ltd., London, England.

normal. Therefore the output is $\frac{15}{11} \times 5$ K.W., or 6.82 kilowatts, to give normal W_c with a primary applied voltage of 1,500 volts.

COMMERCIAL TYPES OF TRANSFORMERS.

107. Core-Type Transformers. Transformers may be classified, according to the relative disposition of the iron and copper, into:

(*a*) Core-type transformers.
(*b*) Shell-type transformers.

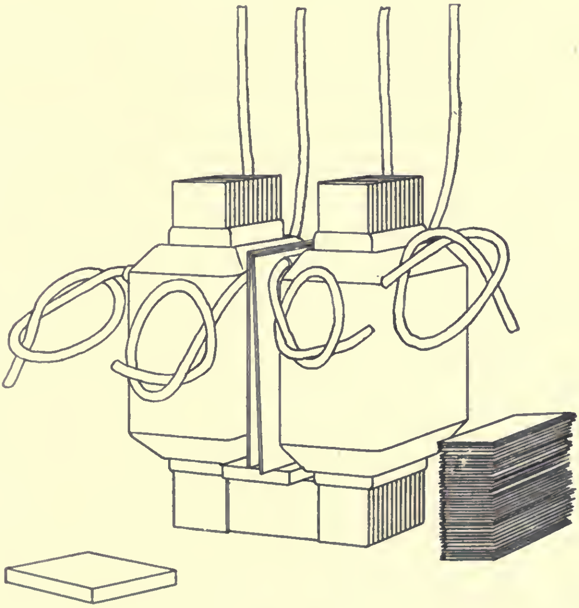


Fig. 216.

Fig. 213 shows a complete core-type transformer without its case; Fig. 214 shows the complete core built up of thin sheet-iron strips, or stampings. The two upright portions of the core upon which the wire coils are placed, as shown in Figs. 215, 216, and 217, are called the *limbs* of the core. The short horizontal parts of the core that do not have windings of wire upon them are called *yokes*. These yokes serve to complete the magnetic circuit, and they are just long enough to give room for the coils as shown in

Fig. 217. Fig. 215 shows the core with its upper connecting yoke removed to permit of the slipping of the coils into position on the core; the left-hand limb of the core is shown wrapped with a thick layer of insulating material in order to prevent electrical contact between the wire of the coil and the iron of the core. Fig. 216 shows the coils in place, and a pile of loose sheet-iron stampings which are used to form the upper connecting yoke.

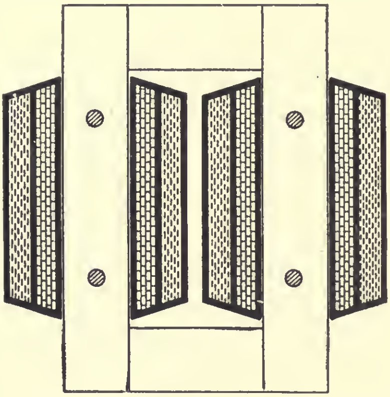


Fig. 217.

Fig. 217 is a sectional view of the completed core and coils; and Fig. 218 is a sectional view of the complete transformer enclosed in a cast iron case. Sometimes this case is filled with oil. Half of the primary coil is placed upon each limb of the core, and half of the secondary coil also is placed upon each limb of the core, as shown by the sectional view, Fig. 217. The terminals of each half of the primary (fine-wire) coil are connected to binding screws on a porcelain connection board mounted on top of the transformers inside the case, as shown at the right in Fig. 218. The terminals of each half of the secondary (coarse-wire) coil are passed through porcelain bushings to the outside of the case as shown at the right in Fig. 218. The half coils of the primary may be connected in parallel or in series according to the value of the voltage applied to the primary; and the half coils

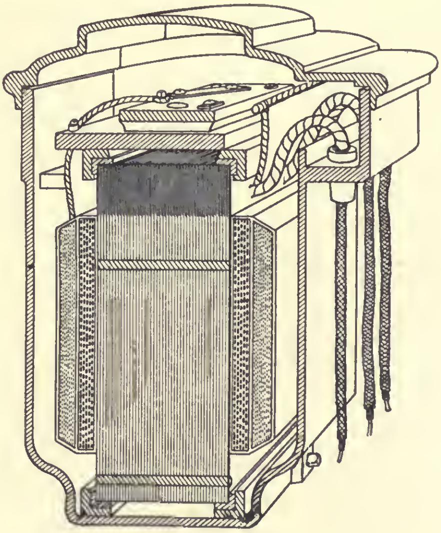


Fig. 218.

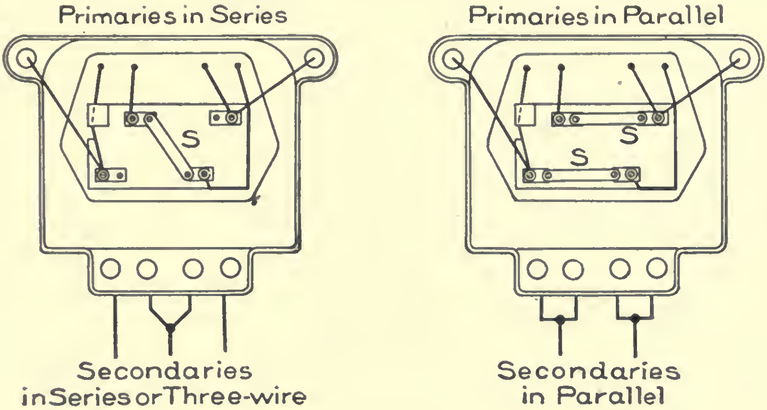


Fig. 219.

of the secondary may be connected in parallel or in series according to the desired value of the secondary voltage, as explained in Article 91.

Fig. 219 is a top view of the transformer with the cover of its case removed showing the terminals of the secondary coils, and the porcelain connection-board to which the terminals of the primary coil are connected. The change from series to parallel connection of the halves of the primary coils, is effected by means of the copper connecting straps S S.

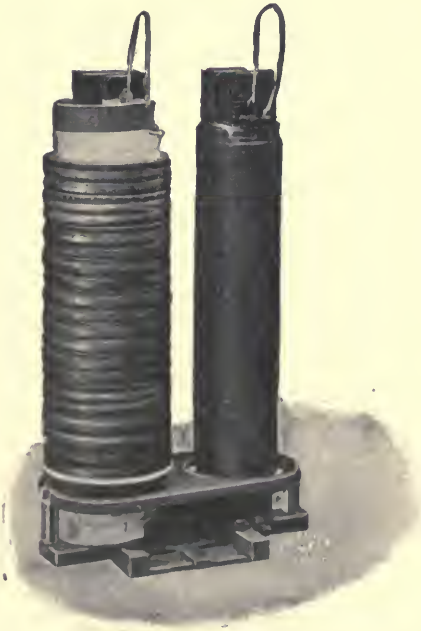


Fig. 220. 100-K.W. Core-Type Transformer in Process of Construction.

The style of core-type transformer illustrated in Figs. 213 to 219 is adopted by several manufacturers for transformers of small output. The style of core-type transformer adopted by the General Electric Company for larger outputs up to 125 kilowatts, is illustrated in Figs. 220 to 224, which shows a 100-kilowatt transformer designed for 60 cycles, for a primary voltage of 30,000 volts, and for a secondary voltage of 2,000 volts. These larger-sized transformers are submerged in tanks of oil, one of which is shown in Fig. 224, and which are made of cast iron, with deep corrugations to facilitate cooling of the tank by radiation. Fig. 222 shows the arrangement of the coils on the core; it also shows the passages between the core and the inside coil, and between the two coils, for the circulation of the oil.

Oil is a better heat-conducting medium than air; it carries heat from a transformer to the containing case much better than air, so that a transformer in oil will show a much lower temperature. The use of oil, moreover, preserves the insulation, keeping it soft and pliable, and prevents oxidation by air; consequently, its use is advantageous in producing proper conditions to maintain uniform core loss

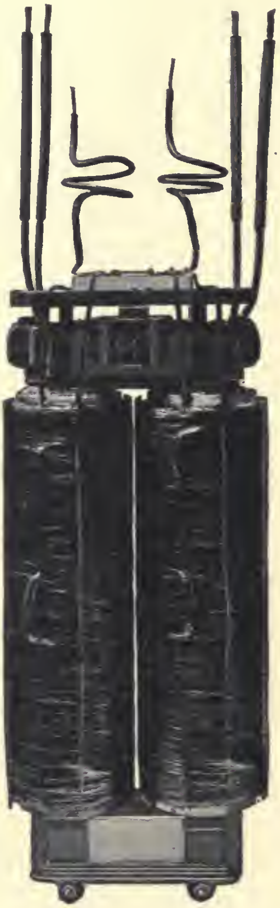


Fig. 221. 100-K.W. Core-Type Transformer; Core, Coils, and Connection Board Complete.

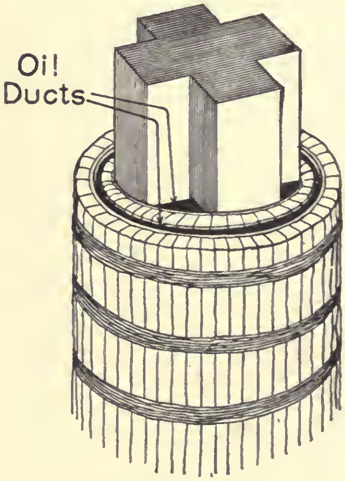
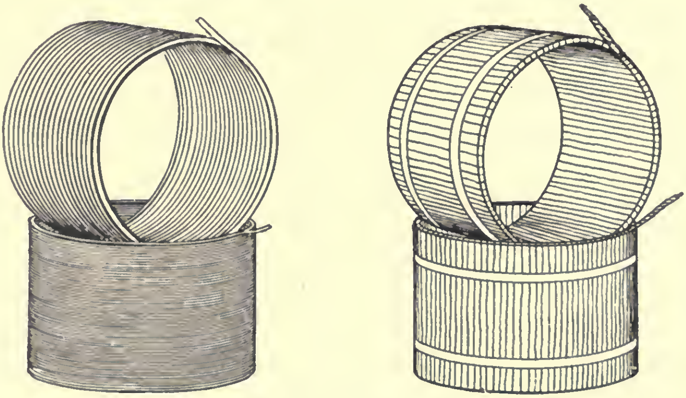


Fig. 222.

and a superior insulation. Furthermore, oil is itself a very good insulator having the valuable property common to all liquid insulators, that it is not permanently damaged by a puncture (from lightning, for example).



Unfinished and Finished Edge-Wound Coils for Core-Type Transformer.

Fig. 223.

108a. Shell-Type Transformers. Figs. 225 to 228 show the general view and structural details of a 5-K.W. shell-type transformer; and Figs. 229 to 231 show the details of a 2-K.W. shell-type transformer. The shape of the core stampings is clearly shown in Fig. 229. The stampings of the 5-K.W. transformer are shown in Fig. 225 clamped together by means of end-plates and bolts, one end-plate having legs that support the entire structure. The stampings of the 2-K.W. transformer are clamped together by means of wedges driven under the ends of the coils; the ends of the wedges appear in Fig. 231. Two sections of the primary coil, and one section of the secondary coil, of the 5-K.W. transformer, are

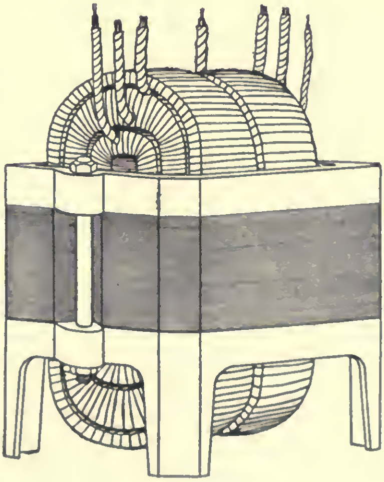


Fig. 225.

shown "nested together" in Fig. 228; the object of the nesting is to reduce magnetic leakage.

In large-sized shell-type transformers, the primary and secondary coils are divided up into many sections, which are nested together with primary and secondary sections alternating. The coils are wound on formers, thoroughly taped and impregnated with insulating compound; and the core is then built up piece by piece around the assembled coils. In building up the core out of the stampings, care is taken to break joints in successive layers.

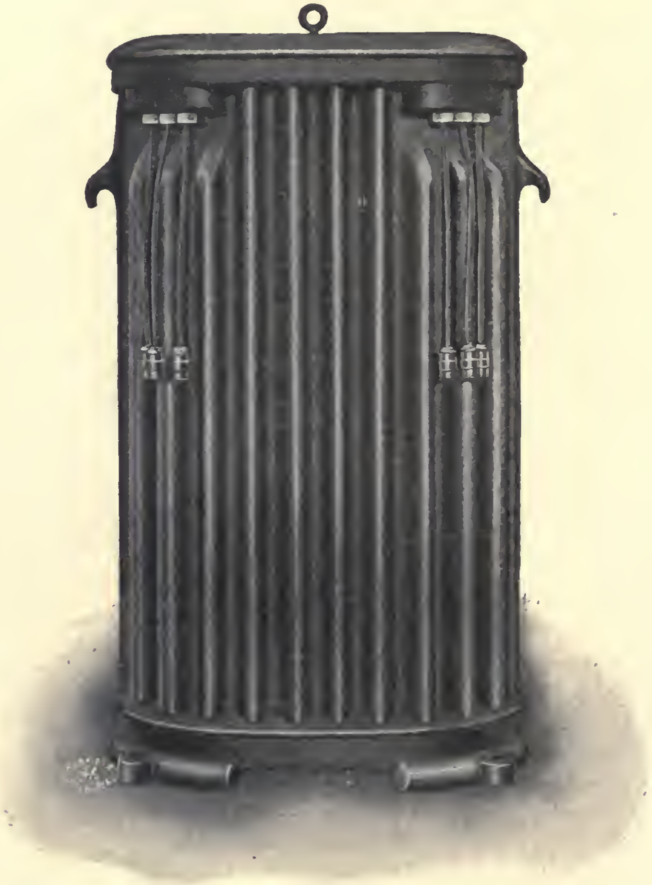


Fig. 224.

Figs. 232 to 239 show constructive details peculiar to very large shell-type transformers.

Fig. 232 represents a complete 800-K.W. Stanley (S .K. C.) transformer with the sides of the containing case removed to show the method of supporting the transformer on the bottom of the case, and to show also the coils of brass pipe through which water is circulated in order that the oil filling the case and surrounding the transformer may be kept cool while the transformer is in operation. The sides of the containing case are made of flat plates of boiler iron which are riveted to the cast-iron base and the top plates and then thoroughly calked. The four eye-bolts shown pass through cover and base plates, and serve for attaching lifting chains to prevent straining of the containing case in moving, and thus to prevent leaks.

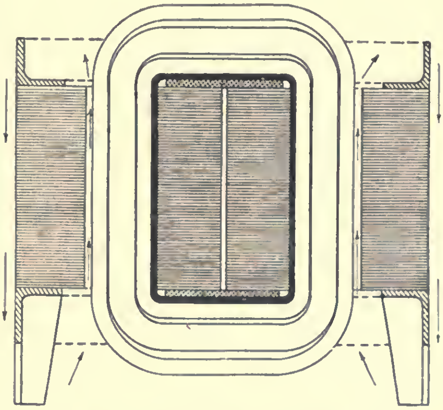


Fig. 226. Vertical Section Through 5-K.W. Transformer, Without Case.

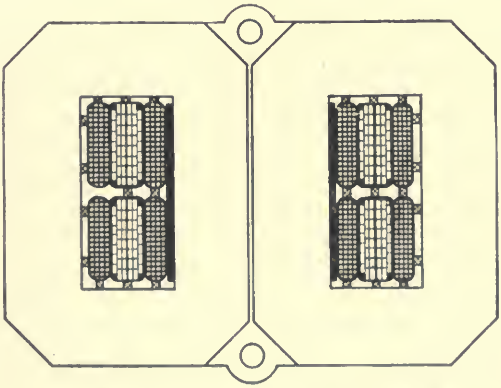


Fig. 227. Horizontal Section Through 5-K.W. Transformer, Without Case.

The transformer core and coils can be removed from the tank without disturbing the cooling coil and its connections. The amount of cooling water at 15° C (59° F) required for the 800-K.W. transformer, is about one gallon per minute, and the temperature of the water at the outlet is about 55° C(131° F).

All the interconnections between the coils are made at the top of the transformer inside of the core, in order to be readily accessible. The main primary and secondary leads are brought up to the terminal boards which are rigidly supported above the coils; the primary board being on one side and the secondary on the other. From these boards the leads are brought out through porcelain insulators in the cover.

Fig. 233 shows the complete 800-K.W. S. K. C. transformer in its oil tank.

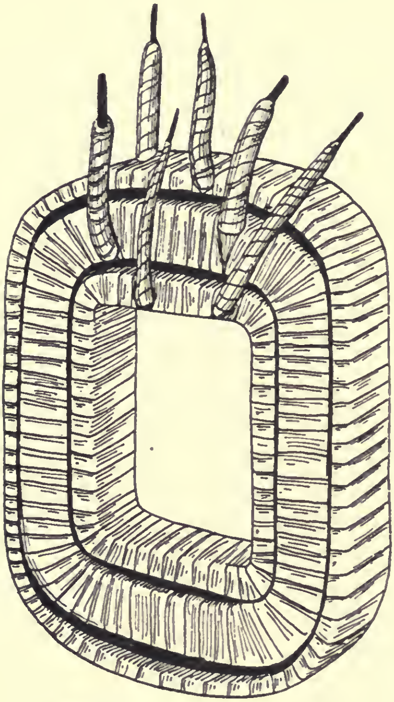


Fig. 228. One-half Set of Assembled Coils for 5-K.W. Transformer.

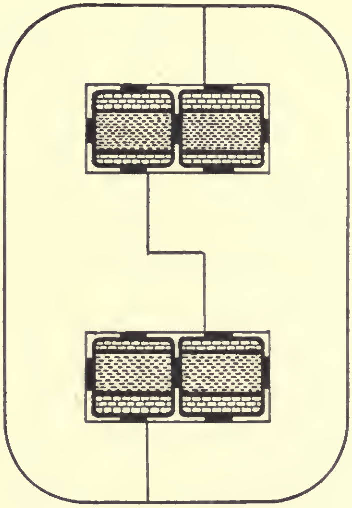


Fig. 229. Cross-Sectional View of Core and Coils for 2-K.W. Transformer.

Fig. 234 shows a large General Electric air-blast, shell-type transformer at that stage of construction where the core stampings are being built up around the coils, the coils being protected by thick strips of insulating material. In this air-blast transformer, air passages or ducts are provided between the layers of the coils, and at intervals, between the core stampings, as shown in the figure. The air for cooling the transformer is admitted at the base, and passes vertically through the ducts in the coils. Air is also admitted to the air ducts in the core through a damper on one side of the transformer, and escapes through the perforations in the casing on the opposite side.

Figs. 235 to 238 show the method of winding the thin sections of the coils for large shell-type transformers; and Fig. 239 is an end view of a large shell-type transformer, showing the ends of the thin coils flared to allow easy access of oil, and showing the thin sheets of insulating material between the coils.

Each thin section of coil is made of two single sections like that shown in Fig. 237. These two single sections are laid together with a sheet of insulation between them; and the inside terminals of the two single sections are soldered together, so that the two outside terminals of the two single sections constitute the two terminals of the double section, as shown in Fig. 238. This double section is thoroughly wound with tape, and is impregnated in a vacuum with melted insulating material. The effect of the vacuum is to extract all the air from the coil so as to allow the melted material to impregnate the coil completely.

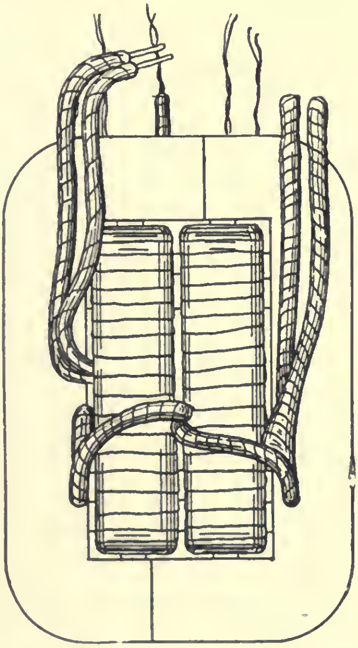


Fig. 230. 2-K.W. Transformer, Core and Coils. End View.

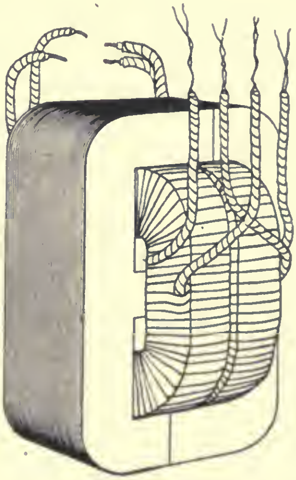
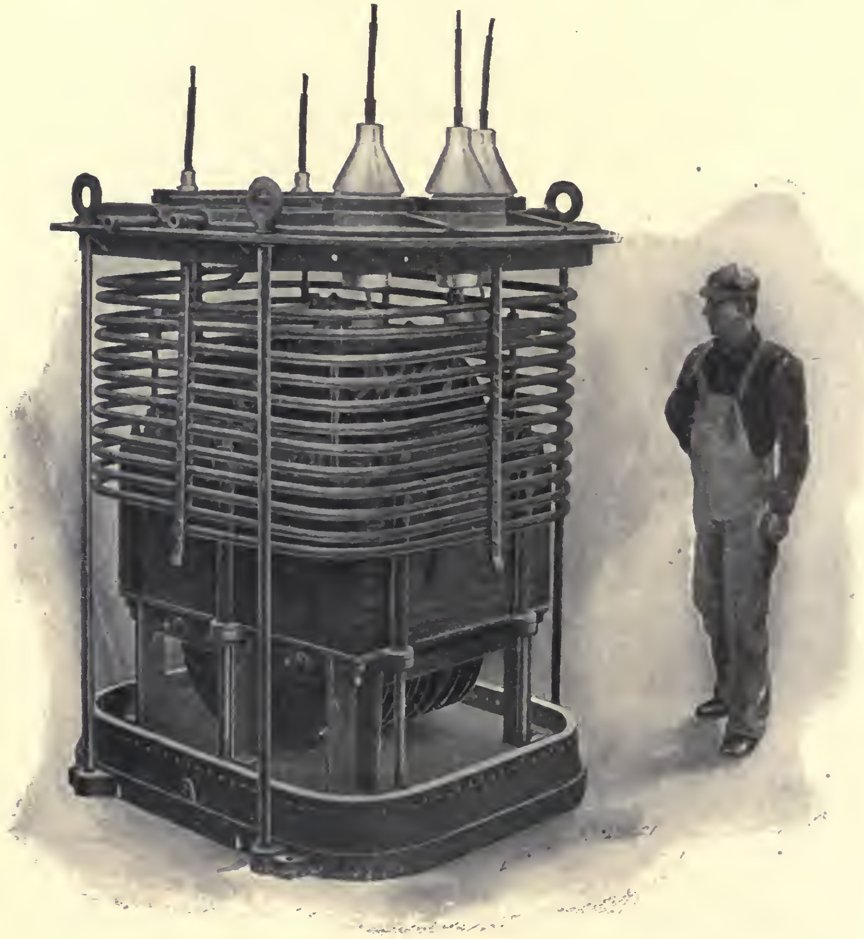


Fig. 231. Perspective View of Core and Coils of 2-K.W. Shell-Type Transformer.

108b. Cooling of Transformers. Transformers of moderate size have large radiating surface compared with their losses. Such transformers, therefore, can radiate the heat due to core losses and copper losses without excessive rise of temperature.

A transformer which is twice as large as a given transformer in length, in breadth, and in thickness, has eight times as much volume but only four times as much radiating surface as the latter. The larger transformer having nearly eight times the losses and four times the radiating surface of the smaller transformer would rise to a much higher temperature than the smaller transformer in order to radiate the heat due to its losses. Large transformers



.00-K.W. S. K. C. Shell-Type Transformer Without Casing; 2,000 Volts Primary and 30,000 Volts Secondary.

Fig. 232.

must, therefore, be provided with special means for cooling. It is much cheaper to provide special cooling devices than to attempt to make the transformer large enough to keep cool by natural radiation.

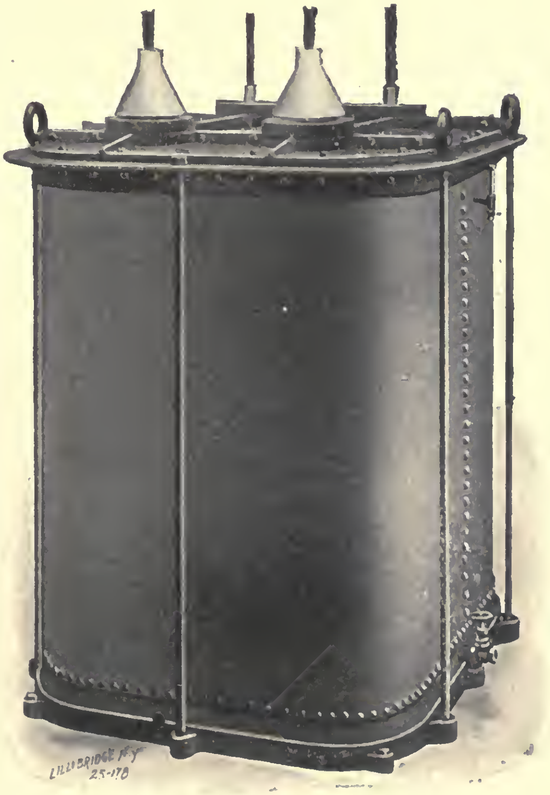


Fig. 233.

Various methods of cooling are adopted in practice, according to which a classification of transformers may be made as follows:

1. Self-cooling dry transformers.
2. Self-cooling oil-filled transformers.
3. Transformers cooled by forced current of air.
4. Transformers cooled by forced current of water.
5. Transformers cooled by combination of above means.

Self-Cooling Dry Transformers. These transformers are usually of small output, and no special means of cooling is provided.

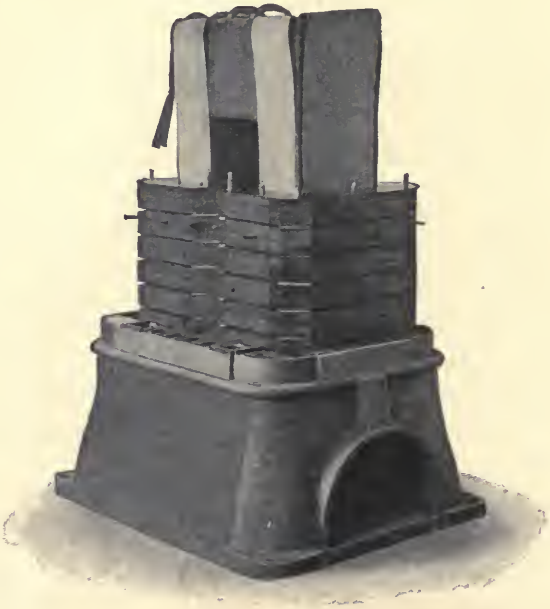


Fig. 234. Shell-Type Transformer in Process of Construction.

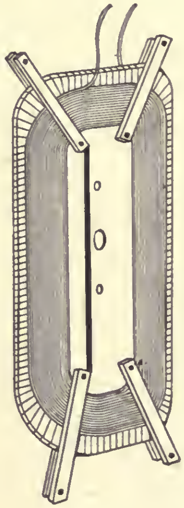


Fig. 235. Coils for Shell-Type of Transformer.

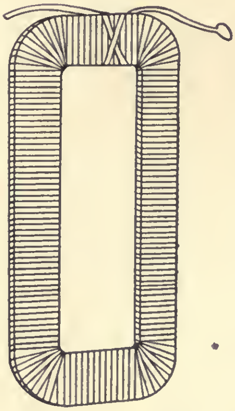


Fig. 236. Coils for Shell-Type of Transformer.

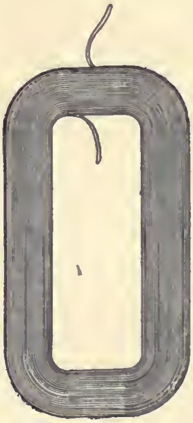


Fig. 237. Single Section of a Coil.

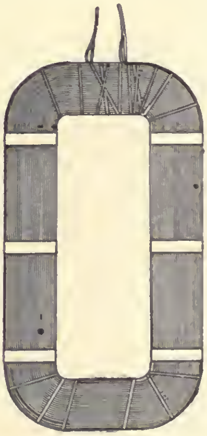


Fig. 238. Two Single Sections Assembled to Form Complete Coil.

the natural radiation being depended upon for cooling. Some larger ones up to 50 K.W., are also made in this way; but they are heavier and more expensive than if specially cooled.

Self-Cooling, Oil-filled Transformers. Transformers of this type are very generally employed, the entire core and coils being immersed in oil. Transformers are practically always enclosed in a cast-iron or sheet-iron case, and this is simply filled with oil. No increase in cooling surface is thereby secured, but the natural circulation of the oil tends to equalize the temperature of the various parts, and carries the heat to the case, from which it is radiated. In most self-cooling types, the case is made with external ribs or corrugations to increase its radiating surface. The large volume of oil also absorbs considerable heat, so that the temperature rises more slowly. Hence, for moderate periods of operation, up to 3 or 4 hours—which is ordinarily sufficient in electric lighting—the maximum temperature would not be reached. Another advantage gained by this arrangement is an improvement in insulation. This is due to the high insulating qualities of the oil itself, and to the fact that a disruptive discharge takes place through it much less readily than through the air that it displaces, distances being the same. This arrangement possesses, moreover, the power of self-repairing any break in the insulation. If ordinary materials, such as cloth or mica, become punctured, they lose their insulating properties, and the apparatus cannot be used until the fault is repaired, which ordinarily involves considerable time and expense. On the other hand, if oil is punctured, it tends to

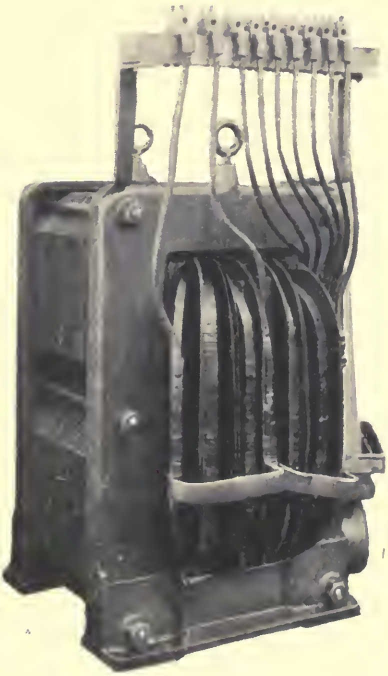


Fig. 239.

close in and repair the break, unless the discharge lasts so long that a charring occurs, which may make a permanent conducting path.

The chief objection to the use of oil is the danger of fire. If a short-circuit occurs inside the transformer, the oil may be thrown out and ignited at the same time; or a fire started in any other way might be made far more disastrous than it would otherwise be owing to the presence of a large quantity of oil. In this way, several power plants have been destroyed by fire with large loss of property. There is no special precaution that will entirely eliminate this risk; but care in locating such transformers, in avoiding overheating, and in protecting the machines by effective lightning arresters, will reduce the hazard.

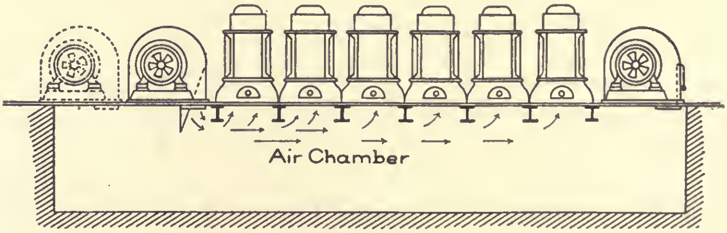


Fig. 240.

Air-Blast Transformers. These transformers are now commonly employed, and have advantages over those of the oil-cooled type, in that the danger of fire is avoided, and the cooling effect can be regulated in accordance with working conditions. They are so constructed that air can circulate through and around the core and coils, the ventilation being forced by a blower driven by a motor. A transformer of 100-K.W. capacity requires about 350 cubic feet of air per minute at a pressure of 0.4 ounce per square inch, the power consumed being less than one-tenth of one per cent of the full-load output of the transformer. The flow of air is controlled by dampers; and the proper amount of air can be determined from its temperature as it issues from the top; ordinarily this temperature should not be more than 20°C above the temperature of the room.

Fig. 240 shows a bank of six large air-blast transformers supported on I beams over an air chamber supplied with air from a fan blower. The air passes in at the bottom of each transformer case, penetrates through ducts in the core and coils, and passes out at the top of the case, as shown in Fig. 241.

Water-Cooled Transformers. Transformers in which water is used for cooling, are also oil-filled in most cases. A continuous flow of cool water is maintained, either through pipes immersed in the oil, through a water jacket formed in the casing, or through the hollow or tubular conductors (primary or secondary) themselves if they are sufficiently large. This is the most effective method of cooling. It is very convenient for water-power plants, the supply of water being at hand; but where a natural flow is not available, pumps or the city water mains may be utilized. It is found that about one-half gallon of water per minute is sufficient for a 150-K.W. transformer. This type requires the least weight of iron and copper for a given output, since its heat is carried away most rapidly.

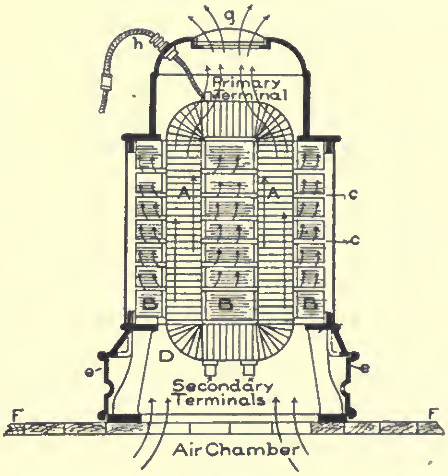


Fig. 241.

Instead of having a flow of water, the oil itself may be drawn off, cooled, and then returned by means of a pump driven by a motor.

Note. In any of these types of transformers depending upon forced circulation of air, water, or oil, *it is vitally important to avoid any stoppage of the flow*, as this is likely to cause a burn-out of the transformer coils.

108c. Series or Current Transformers. It was pointed out in article 94, that a transformer intended for giving an accurately fixed ratio between primary and secondary currents, must be so designed as to have a very small magnetizing current. Fig. 242 shows a general view of a small current transformer designed for use in connection with a switchboard ammeter, and made by the Wagner Electric Manufacturing Company, of St. Louis, Mo. The core of this transformer consists of a number of ring-shaped stampings assembled on a double-barreled porcelain tube. In general appearance it resembles the core of a drum armature.

The main that carries the large alternating current to be measured, passes through one hole in the porcelain tube, and constitutes the primary coil of the transformer. The secondary winding consists, say, of ten loops of relatively small wire threaded through the other hole in the tube. The terminals of the secondary coil are connected to the switchboard ammeter. The secondary current (ten turns of wire being used in the secondary coil) is one-tenth of the current in the main; and the ammeter readings must therefore be multiplied by 10 to give the current in the main, or the ammeter may be calibrated to read the current in the main directly.

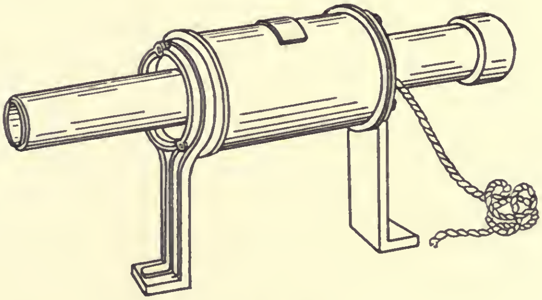


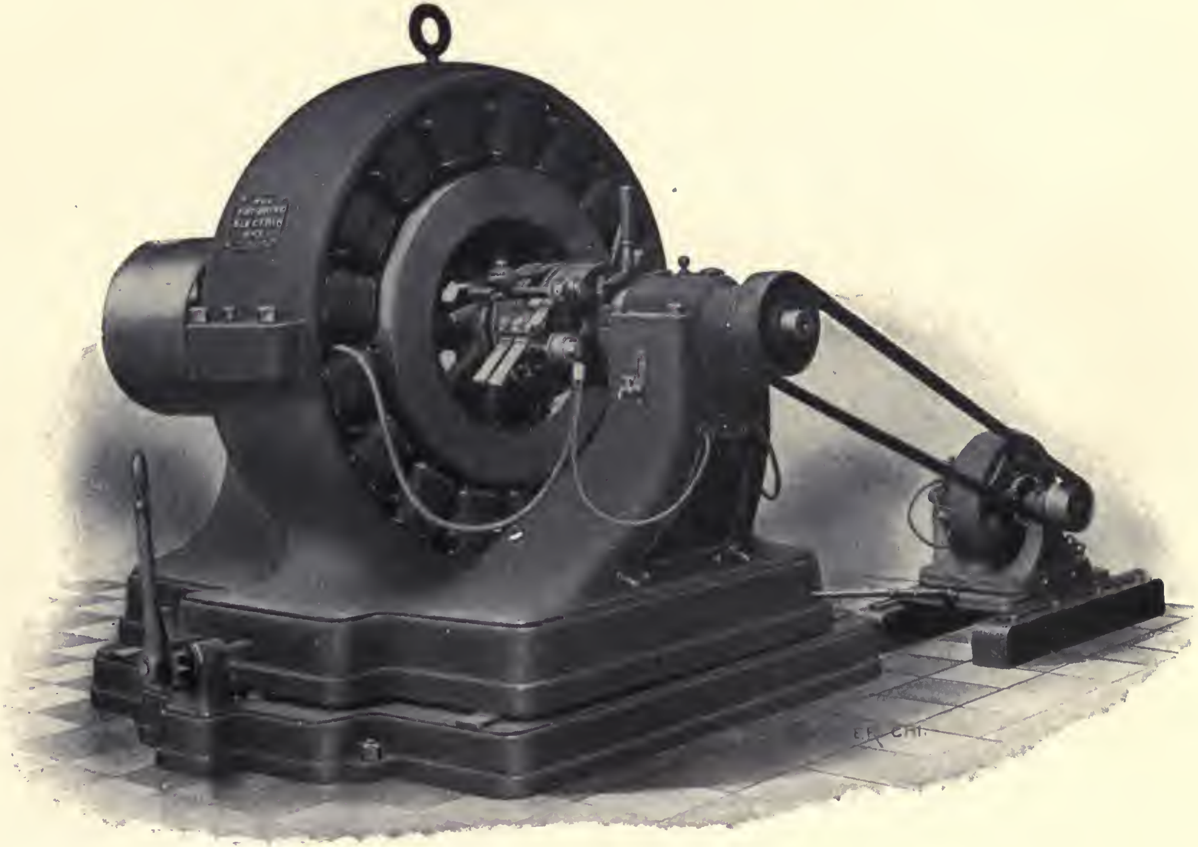
Fig. 242.

The electrical connections for a series transformer have been described in article 94. In Fig. 194 the coil A, in series with the secondary coil S, may represent the switchboard ammeter.

The question may arise as to why the switchboard ammeter is not connected as a shunt across the terminals of a low-resistance link inserted in the main circuit whose current is to be measured, exactly as in the case of switchboard ammeters for direct currents. There are two reasons why this arrangement would not be permissible:

(*a*) An alternating current does not divide between two branches of a circuit in inverse proportion to the resistances of the branches, when either branch has inductance. Therefore the reading of a shunted alternating-current ammeter cannot be multiplied by a constant factor to give the total current in the main circuit.

(*b*) It is objectionable to have the ammeter in electrical connection with high-voltage mains. The use of the series transformer is therefore preferable on the grounds of both accuracy and of safety.



16-POLE, 140-CYCLE ALTERNATOR.

Fort Wayne Electric Works.

108d. Constant-Current Transformers. The constant-current transformer is a transformer specially designed to take a nearly constant current at varying angles of lag from constant-voltage mains, and to deliver a constant current from its secondary coil to a receiving circuit of variable resistance. The action of this transformer is as follows:

The primary coil P and the secondary coil S of the transformer surround a long, laminated-iron core, as shown in Fig. 243. This core, and the yokes at the top, bottom, and sides, form a double magnetic circuit. The magnetic flux Φ, which at a given instant passes through the primary coil, flows partly through the secondary coil as the useful flux U, and partly leaks across between the primary and secondary coils as the leakage flux L.

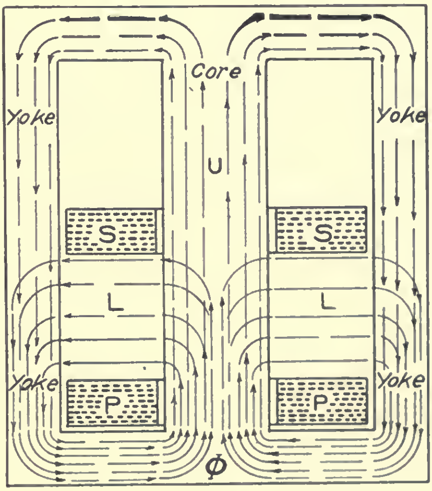


Fig. 243.

The leakage flux L, in flowing across the air spaces from core to yokes, constitutes an intense magnetic field which pushes up on the secondary coil. The secondary coil is suspended, and partly counterbalanced by a weight, so that the upward push of the leakage flux just suffices to sustain the coil. If the resistance of the secondary receiving circuit is increased, the immediate result is to reduce the secondary current below its normal value, which lessens the upward push of the leakage flux on the secondary coil. The secondary coil then, owing to the unbalanced action of the weight, moves down towards P, the leakage flux is lessened in amount, and the useful flux U is increased in amount. This increase of useful flux increases the induced electromotive force in S; and the downward movement of S continues until the induced electromotive force in S is large enough to produce the normal value of the current through the increased secondary resistance.

Similarly, a decrease of resistance of the secondary receiving circuit causes a momentary increase of secondary current which increases the upward push on the secondary coil. This coil moves upwards until the secondary current is reduced to the normal value.

The following table shows the approximate constancy of secondary current in a constant-current transformer supplying current to a varying number of arc lamps connected in series to its secondary coil:

TABLE V.

Constant-Current Transformer Data.

Test of a 50-light, 6.6-ampere constant-current transformer, frequency 60 cycles per second.

Primary Volts.	Number of Lamps.	Volts per Lamp.	Secondary Volts.	Secondary Amperes.
2,200	50	76.6	3,830	6.60
2,200	40	77.6	3,105	6.70
2,200	30	77.2	2,315	6.67
2,200	25	81.4	2,035	6.65
2,200	20	84.2	1,685	6.65
2,200	15	86.0	1,290	6.65

With 50 lamps, the primary current is 14.83 amperes; and with 20 lamps, is 14.78 amperes. In the latter case, the primary current lags 71° behind the primary applied voltage; the power factor corresponding to this angle is 0.326; and the power received from the mains is $2{,}200 \times 14.78 \times 0.326 = 10{,}600$ watts, or 530 watts per lamp. With 40 lamps, the primary current lags 55° behind the primary applied voltage; the power factor corresponding to this angle of lag is 0.575; and the power received from the mains is $2{,}200 \times 14.81 \times 0.575$ which is equal to 18,800 watts, or 470 watts per lamp. The efficiency of the transformer with a 50-lamp load was 93.9 per cent and with a 20-lamp load, it was 85.7 per cent.

Fig. 244 is a general view of the mechanism of the double-coil (two primaries, and two secondaries), constant-current transformer of the General Electric Co.; and Fig. 245 shows the transformer in its containing case.

The mechanism of the transformer is surrounded by an iron case, providing ample cooling surface. The working parts of the transformer are immersed in oil, which not only acts as an insulator, but assists in conducting away the heat.

Within the working limits, the magnetic repulsion between the fixed and moving coils of the system for a given position, is proportional to the current flowing in the coils. The transformer, therefore, can be adjusted to maintain any current, simply by changing the amount of counterweight.

In transformers having but one moving coil, the counterweight is equal to the weight of the coil less the electrical repulsion; and a reduction in the counterweight will produce an increase in the current.

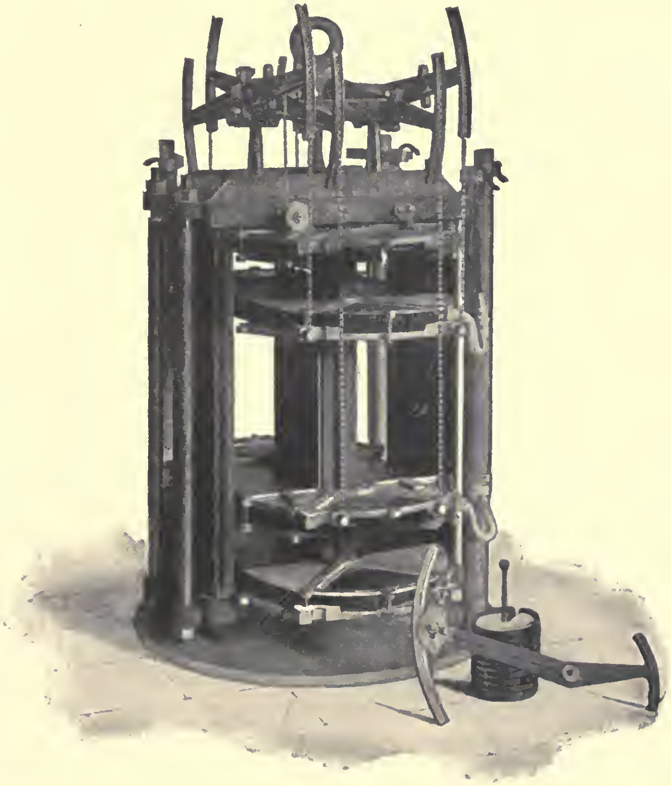


Fig. 244.

In transformers having two primary and two secondary coils, as in Fig. 244, the movable secondary coils are balanced one against the other by a system of double-rocker arms supported on knife edges. The weight necessary to balance the repulsion between the primary and secondary coils is carried on a small auxiliary lever (shown with its adjustable weight in the foreground in Fig. 244); also supported on knife edges. In this case, a decrease in the counterweight is followed by a decrease in the current.

The arc on the counterweight lever is made adjustable because the repulsion exerted by a given current flowing in the coils is not the same for all positions of the coils, being greater when the primaries and secondaries are close together and less when the primaries are separated. By means of the adjustable arc, the effective radius of the balancing weight is made to change as the coils move through their working range. When the primary and secondary coils are separated by the maximum distance, the

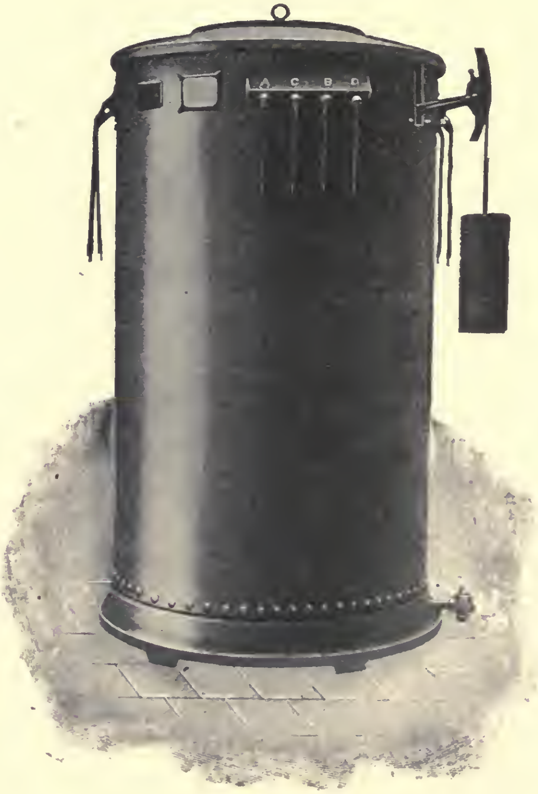
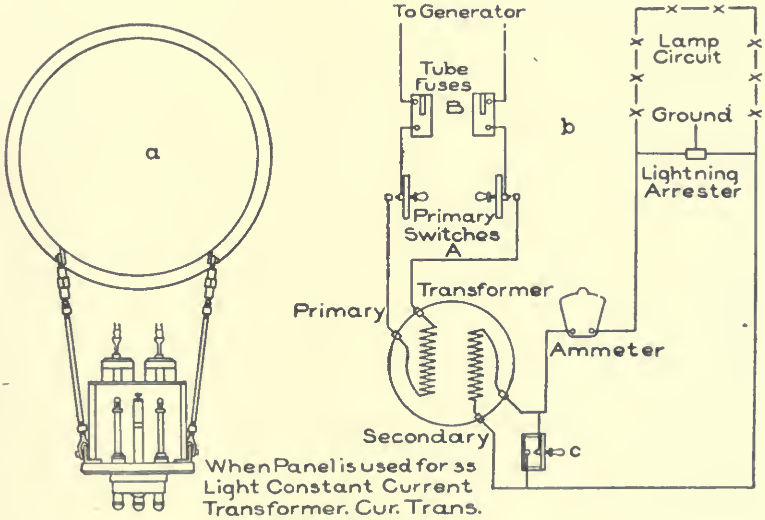


Fig. 245.

resultant force tending to draw them together should be less than when they are close together.

Regulation of Constant-Current Transformers. When current flows in the primary and secondary coils, the mutual repelling forces separate the coils until equilibrium is restored. The current corresponding to the position of equilibrium may be adjusted by changes in the counterweights, and the coils will then always take such a position as will maintain that current constant in the secondary coils, regardless of the external resistances to which the coils are connected. With any current less than normal, the repelling force diminishes, and the primary and secondary coils approach each other, thus restoring normal current. As soon as the secondary current exceeds normal, the resultant pull exerted by the counterweight and coils is overcome, and the secondary coil moves away from the primary, again restoring normal current. Transformers of this design can be made to maintain constant current even more accurately than the constant-potential transformer maintains uniform potential.



When Panel is used for 35 Light Constant Current Transformer. Cur. Trans. is used with Ammeter.

Fig. 246.

In Fig. 246 are shown (*a*) the ground plan of the transformer and switchboard, with its braces attached to the transformer case;

and (*b*) the connections of the primary coil through switches and fuses to a constant-voltage generator; also the connections of the secondary coil through an ammeter to the lamp circuit. The short-circuiting switch C is used to put out the lights by short-circuiting the secondary coil of the transformer. The effect of short-circuiting the secondary coil is to cause only a very slight increase of current to flow through the transformer primary.

Fig. 247 shows front and back views of a one-panel switchboard for a 25- or 35-light transformer. The switchboard is made of highly insulating blue Vermont marble. The switches are of the "tubular expulsion" type, designed to open high-voltage circuits and to ensure suppression of the arc. The ammeter may be cut into either circuit of a multi-circuit transformer supplying current to two or more circuits of lamps, by the jack shown in Fig. 247. On the back of the board are mounted the "tubular expulsion" fuses and current transformers for the ammeter. The current transformers have a 1 : 1 ratio; and they are used merely to permit of the complete insulation of the ammeter from the high-voltage secondary mains (lamp circuit).

108e. Transformer Fuse Blocks. The safety fuse links designed to protect a transformer from burn-out in case of short-circuit, are usually placed in circuit with both primary and secondary coils. The fuse links connected in circuit with the high-voltage coil are usually encased in a porcelain tube which encloses the arc that is formed when the fuse melts; and the expansion of the highly heated vapors in the tube extinguishes the arc by what is called "expulsive" action.

The tubes containing the fuses are usually provided with brass terminals for the fuses, the terminals projecting as blades from one side of the tube. With fuse and terminals complete, the tube is pushed home in a receptacle containing metal spring clips that receive the fuse terminals somewhat after the manner of an ordinary knife-switch.

When the fuse melts or "blows", the tube carrying the fuse and terminals, is withdrawn from the receptacle. A new fuse may then be put in place without danger to the attendant, after which the tube and fuse may be replaced in the receptacle.

In small transformers, the fuse receptacles usually form part of the containing case; but in large transformers the fuse receptacles are, as a general thing, entirely separate from the transformer, and are mounted at any convenient point near the transformer—for example, on a cross-arm, or on the pole where the transformer is placed. In the case of transformers for use out-of-doors the fuse receptacles always consist of waterproof cases of cast iron or porcelain. Figs. 248 and 249 show a single-pole transformer fuse block. It is constructed entirely of porcelain.

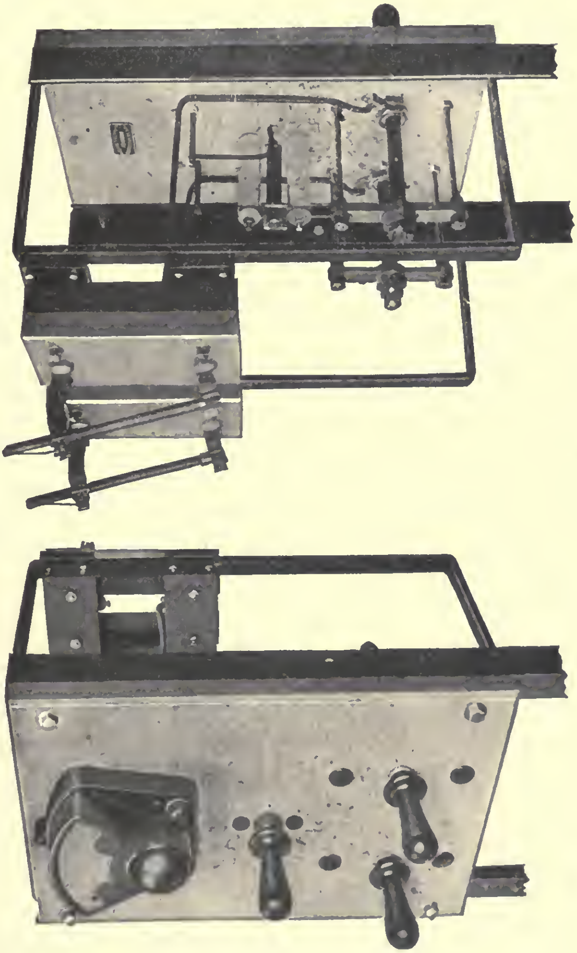


Fig. 247.

The fuse is mounted in a hole which passes lengthwise through the lug projecting from the under side of the cover. The ends of the fuse link connect to the brass screws of which the large heads project from the ends of the lug. These screw heads make connection to spring clips in the case

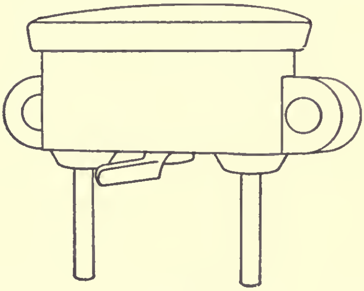


Fig. 248.

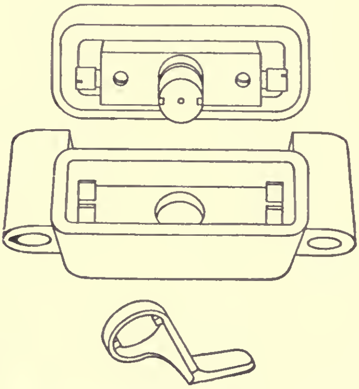


Fig. 249.

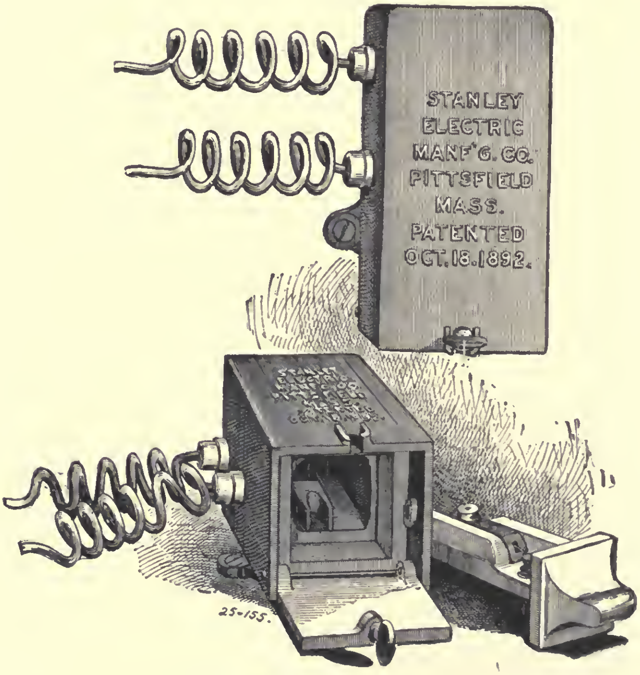


Fig. 250.

proper, and the spring clips connect with the ends of the wires leading out from the receptacle. The hot vapors which are expelled when the fuse melts, pass out of a hole in the porcelain knob that projects through the opening at the bottom of the receptacle. The two parts of the block are fastened together by a malleable-iron screw clamp, shown in Fig. 249.

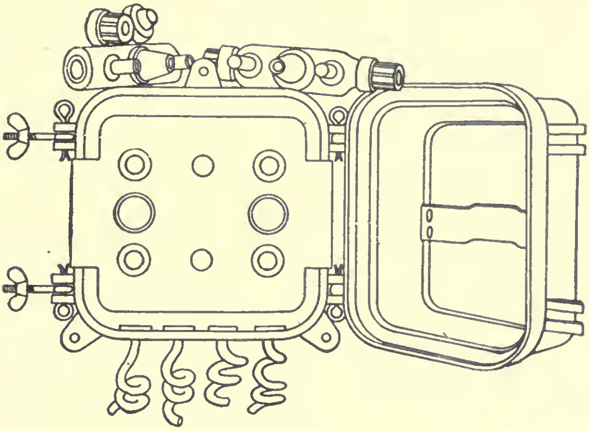


Fig. 251.

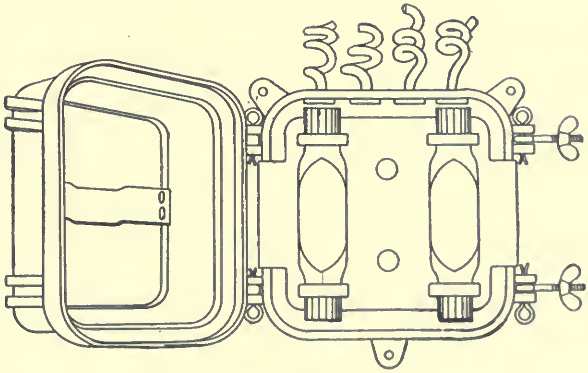


Fig. 252.

Fig. 250 shows a single-pole transformer fuse block. The containing case and cover are of cast iron; the receptacle on the inside is of porcelain; and the fuse carrier is a porcelain block having metal terminals that make connection with spring clips in the receptacle.

Figs. 251 and 252 show a double-pole transformer fuse block. The case and cover are of cast iron; the receptacle plate is of porcelain; and the fuse supporters are porcelain tubes with side vents, as in Figs. 248 and 249.

Mounting of Outdoor Transformers. Fig. 253 shows a transformer in its water-tight containing case, mounted on a pole, with its primary coil connected through a double-pole fuse block to 1,100-volt mains, and its two-coil secondary connected to Edison three-wire mains for supplying incandescent lamps in a near-by building. Two suspension hooks A, made of heavy strap iron, are attached to the back of the transformer case by slipping the bolt-heads B into the sockets C, after which the nuts are screwed tight.

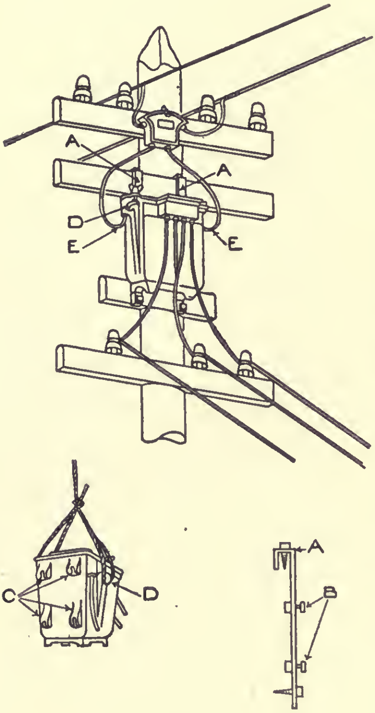


Fig. 253.

The transformer is hoisted to its position on the building or cross-arm by means of a rope or chain, which is slipped over the two hoisting lugs D. When the transformer is hoisted into position, the suspension hooks are slipped over the cross-arm, and screwed fast by means of lag screws. The lead wires from the primary coil are connected to the lower fuse-box leads, and the upper fuse-box leads are connected to the mains. The wires from the secondary coils are led into the building where the secondary fuses are placed.

TRANSFORMER TESTS.

109. Heat Test. The simplest method of performing this test is to connect the primary coil of the transformer to mains giving the rated voltage and frequency of the transformer, and to load the secondary with a bank of lamps or a water rheostat, adjusting the resistance so as to get rated full-load current from the transformer. The run should be continued until an approximately constant temperature is reached.

The objection to loading the transformer in the way described is that it requires taking the full rated power from the transformer, which power, therefore, is usually wasted. The following method, accordingly, is preferable.

If two transformers of the same voltage and rated capacity are available, the test may be made on the two simultaneously by what is known as the **motor-generator** method. The arrangement is shown in Fig. 254.

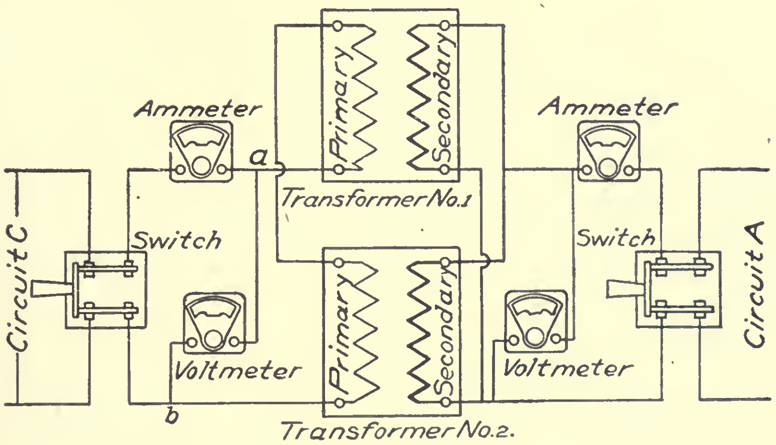


Fig. 254.

The two secondaries are connected in parallel, and are excited from a low-voltage circuit A at normal voltage and frequency; consequently normal voltage is induced in each primary winding. The two primaries are connected in series, but in such a way as to oppose each other. The resultant voltage between the points *a* and *b* will then be zero, notwithstanding the fact that full voltage exists between the terminals of each transformer secondary. Therefore, if the points *a* and *b* be joined together no current will flow. If, however, instead of being joined, these terminals are connected to the terminals of the circuit C, any voltage impressed at C will produce a current in the circuit of the primary coils independent of the voltage existing in each of the primary coils. Since each transformer is in effect short-circuited by the other, it follows that approximately twice the impedance voltage* of one transformer impressed at C will cause full-load current to flow through the primaries and secondaries of both. Under these conditions, the transformers will run at full load, while the total energy required for the test amounts to merely the losses in the two. The circuit A supplies the excitation current and core losses, the circuit C the full-load current and copper losses.

The auxiliary electromotive force impressed at C may be derived from the same source as the electromotive force at A, by means of a transformer. A regulating resistance must be connected in series with it to allow adjustment of the electromotive force at C until the ammeter registers full-load current.

The important temperatures to be observed are those of the coils, core, and room. The temperature of the case and of the oil may be observed as checks.

The determination of the temperature of the coil may be made by thermometer or by measurement of resistance. If a transformer has remained in a room of constant temperature many hours, so that the temperature is approximately uniform throughout, thermometer measurement indicates quite accurately the temperature of the windings. If, however, the transformer is radiating heat, as during the heat run, the actual temperature of the copper coils will be much greater than the temperature of surface insulation.

If we know the "cold" resistance, as measured under the first of the above conditions, and the temperature of the coil at the time of measurement, we have a means of finding the "hot" temperature of the coil by measuring its "hot" resistance. The rise in temperature above the temperature at which the "cold" resistance was measured, may be determined from the equation,

$$R_x = R_t \, [1 + 0.004 \, (x - t)],$$

in which R_t is the "cold" resistance, R_x is the "hot" resistance, and $x - t$ is the rise in the temperature expressed in degrees centigrade. The temperature coefficient for commercial copper wire is taken as 0.004.

If the room temperature differs from 25° C the observed rise in temperature should be corrected by 0.5 per cent for each degree centigrade. Thus, with a room temperature of 35° C, the observed rise should be decreased by 5 per cent; and with a room temperature of 15° C, the observed rise should be increased by 5 per cent.

110. Core-Loss and Exciting-Current Test. For this test, the transformer is connected as shown in the diagram, Fig. 255, the primary being left on open circuit. Theoretically the test may be carried out with *either* coil connected to mains of the proper voltage and frequency. In practice, however, it is better, from the standpoint both of convenience and of safety, to connect the *secondary* coil.

---

*Note. The impedance voltage of a transformer is the electromotive force which must be applied to the primary coil to produce full-load current in both coils when the secondary coil is short-circuited. This voltage is from 2 per cent to 8 per cent of the rated full-load primary voltage. See article 112.

The electromotive force is adjusted by means of the variable resistance until the voltmeter indicates rated secondary voltage. The ammeter then indicates the exciting or no-load current; and the wattmeter indicates, very closely, the core loss.

111. Resistance of Coils. The resistance of a coil of a transformer may be measured by the ordinary drop-of-potential method. This method consists in passing through the coil a direct current, the value of which is noted by an ammeter, while the drop of potential across the coil is measured by a voltmeter. Then the resistance is $R = \frac{E}{I}$. Knowing the resistance of the coils, we can determine the drop in potential due to resistance, under load. This loss of electromotive force is usually expressed in per cent of the electromotive force supplied to the primary.

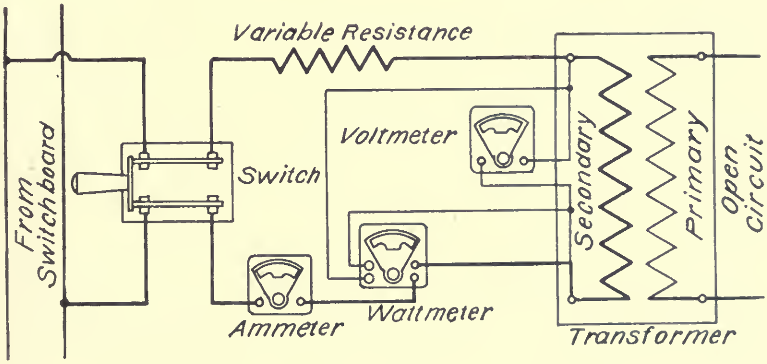


Fig. 255.

112. Impedance. To determine the impedance voltage, the transformer is connected as shown in Fig. 256. As the impedance voltage is not very large—varying from 2 per cent to 8 per cent of rated primary voltage in standard transformers—a much more accurately readable deflection of the voltmeter will be obtained if the primary coil is connected to the mains. As will be seen by referring to Fig. 256, the secondary coil is short-circuited. The primary coil is connected, in series with an adjustable resistance, to the low-tension mains. The resistance is slowly cut out, until full-load current flows in the coil, as indicated by the ammeter. Then the voltmeter indicates the impedance voltage. This should be expressed in per cent of the normal voltage of the coil. From the equation,

$$I = \frac{E}{\sqrt{R^2 + \omega^2 L^2}},$$

the primary impedance, inductance, and reactance can be computed, provided R is known.

113. Efficiency Calculation. The efficiency of any piece of apparatus at a given load is equal to the output divided by the input. The input is equal to the output plus the losses. The efficiency may then be defined as the ratio of *the output* to *the output plus the losses.* In nearly every case the efficiency can be determined more accurately by measuring the losses, and then computing the efficiency according to the second definition, than by attempting to measure the total output and input, and then taking their ratio.

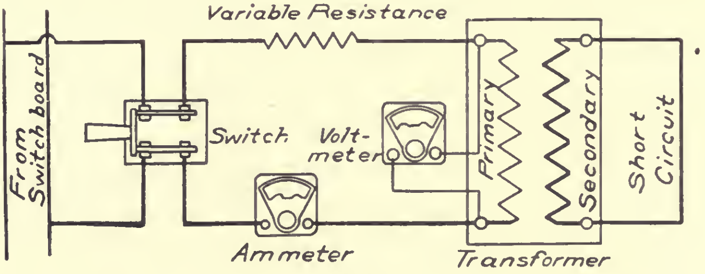


Fig. 256

The losses in a transformer are discussed in article 102.

Example. A given 5 K.W. transformer is rated at 2,000 volts primary, and 200 volts secondary, at a frequency of 60 cycles per second. The coil resistances are found by measurement to be:

Primary coil resistance	10.1 ohms.
Secondary coil resistance	0.067 ohms.

At full load:

Full-load currents are:

Primary current	2.5 amperes.
Secondary current	25.0 amperes.

Core loss, as determined by test..............70 watts.
Copper losses at full-load are:

Primary loss = $R'I'^2 = 10.1 \times (2.5)^2 =$......63 watts.
Secondary loss = $R''I''^2 = 0.067 \times (25)^2 =$..42 watts.

Total loss at full-load.......................175 watts.
Full-load output..........................5,000 watts.
Full-load intake..........................5,175 watts.
Full-load efficiency 5,000 ÷ 5,175 =........ 96.6 per cent.

At half-load:

Total RI^2 loss...............................26 watts.
Core loss.................................70 watts.
Total loss...................................96 watts.
Half-load output.........................2,500 watts.
Half-load intake..........................2,596 watts.
Half-load efficiency, 2,500 ÷ 2,596=.........96.3 per cent.

The all-day efficiency of a transformer is the ratio of the output of work (watt-hours) during the day to the total input of work (watt-hours). The usual conditions of practice will be met if the calculation is based upon 5 hours at full load, and 19 hours at no load.

Output:

5 hours at full load = 5 hours × 5,000 watts = 25,000 watt-hours
19 hours at zero load = 0 watt-hours
Total output in 24 hours = 25,000 watt-hours

Input:

5 hours at full load = 5 hrs. × 5,175 watts = 25,875 watt-hours
19 hours at zero load = 19 hrs. × 70 watts = 1,330 watt-hours

The zero load intake is but very little more than core loss, since $R'I'^2$ is negligible at zero load.

Total intake in 24 hours 27,205 watt-hours
All day efficiency 25,000 ÷ 27,205 = 91.9 per cent

114. Polarity Test. Transformers are generally designed so that the instantaneous direction of flow of the current in certain selected leads is the same in all transformers of the same type. For example, the transformer shown in Fig. 257 is designed so that the current at any instant flows into lead A and out of lead C. Such transformers run properly in parallel when similar primary and secondary leads on different transformers are connected together. The primaries of two transformers A and B are connected to supply mains, the connections of one primary being made without reference to the connections of the other. It is desired to determine (1st) how the secondaries are to be connected in parallel to supply current to one and the same receiving circuit; and (2nd) how the secondaries are to be connected in series to supply current to a receiving circuit. This test is made as follows:

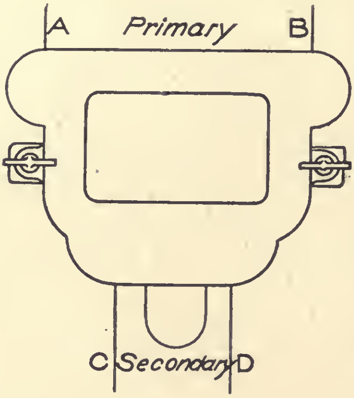


Fig. 257.

Connect a terminal (say *a*, Fig. 258) of the secondary of one transformer to one terminal *c* of the secondary of the other transformer. Then connect two 110-volt lamps in series (or a voltmeter) to the other two terminals *b* and *d*. If the lamps do not light (or if the voltmeter gives no deflection), then (1st) the terminals *a* and *c* are the proper ones to connect together to one service main; and the terminals *b* and *d* are to be connected together to the other service main; and (2nd) the terminals *a* and *c* are not the proper ones to be connected together, but *b* and *c* are properly connected together in order to connect the two coils in series, the other two terminals *a* and *d* being connected to the service mains.

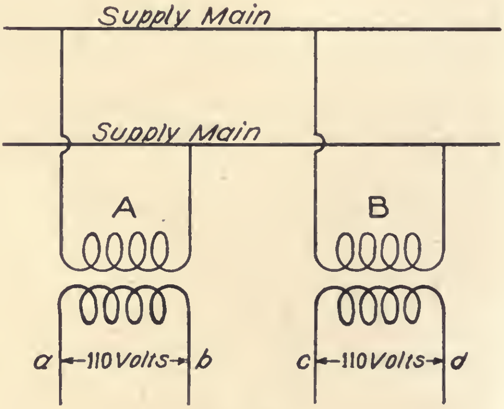
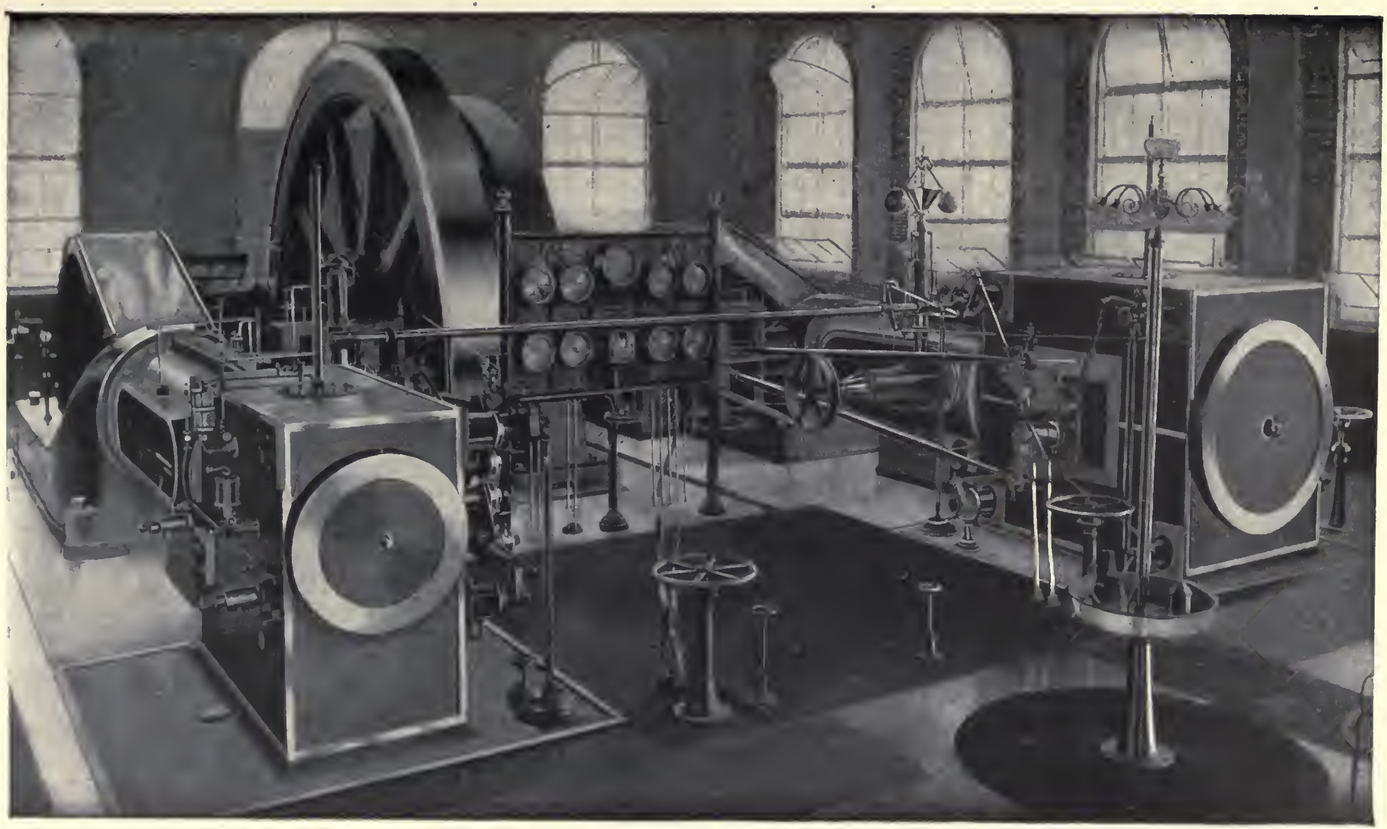


Fig. 258.

THE ROTARY CONVERTER.

115. The Rotary Converter is a machine for converting alternating current to direct current, or *vice versa*. The importance that such machines have now assumed in the electrical industry is due to several causes :



CROSS-COMPOUND CONDENSING CORLISS ENGINE DIRECT-CONNECTED TO A THREE-PHASE ALTERNATING CURRENT GENERATOR.

C. & G. Cooper Company.

(*a*) It is necessary, for economic reasons, to use alternating current at high voltages in long-distance transmission, as explained in article 4. Therefore, rotary converters are required for changing the alternating current into direct current for use in electric railway motors, which must be supplied with direct current from the trolley wire at points at a distance from the power house.

(*b*) Rotary converters are needed for charging storage batteries in places where the central station supplies alternating current, and inverted rotaries are necessary for factory driving with alternating-current motors in cases where direct current only is supplied by central stations.

(*c*) Direct current is necessary in many of the chemical and electro-metallurgical industries such as the electrolytic reduction of aluminum from its ores, the electrolytic refining of copper, etc. If alternating current is generated and transmitted to these establishments, it must be converted into direct current before it can be utilized.

116. Comparison of the Rotary Converter and the Direct-Current Dynamo. In general appearance and construction, the rotary converter resembles the direct-current generator very closely. The chief outward difference is the addition of a number of collector rings concentric with the shaft on one side of the armature, and the commutator is very much larger than in the ordinary direct-current generator. Another point of difference is in the relative dimensions of the magnetic circuit, including yoke and magnet cores, which are smaller than would be usual or desirable in ordinary direct-current generators.

Under the usual condition of running, the armature is driven, as in a simple synchronous motor, by alternating current supplied to the collector rings from an external source. While so revolving direct current can be taken from brushes bearing upon the commutator.

The current in the armature of a rotary converter may be thought of as the difference between the inflowing alternating currents and the outflowing direct current. The average value of the current in a given armature conductor is therefore smaller in value than in the corresponding direct-current generator, and the heating effect (RI^2) is correspondingly less. Furthermore, the magnetizing action of the inflowing alternating current upon the armature is about completely neutralized by the magnetizing action of the outflowing direct current. Therefore a larger number of smaller conductors may be wound upon a given armature core, if the armature is to be used for a rotary converter, than would be permissible if the armature were to be used for a direct-current generator. That is, the allowable power output of a machine of given size is not limited to so small a value if the machine is to be used as a polyphase rotary converter, as it would be if the machine were to be used as a direct-current generator.

The following table gives the power ratings which a machine that would be rated 100-K.W. if used as a direct-current generator has, when it is used as a single-phase, three-phase, two-phase (four-ring), and six-phase converter respectively.

TABLE VI.

Power Ratings of Rotary Converters in Kilowatts.

Continuous-current dynamo.	Single-phase converter.	Three-phase converter.	Four-ring converter.	Six-phase converter.
100	85	132	162	192

117. To Make a Direct-Current Dynamo into an Alternator.

Consider an ordinary bipolar* direct-current dynamo. Imagine two opposite commutator bars of the machine to be marked *a* and *b* respectively (see Fig. 259). Let the field magnet of the machine be excited, and the armature be driven at a speed of *n* revolutions per second, in a counter-clockwise direction, as shown by the arrow. At a given instant the marked bars will be midway between the direct-current brushes, as shown in the figure. Let us call the position of the armature at this instant the position A, Fig. 260, and let us consider the way in which the electromotive force between the given pair of commutator bars *a* and *b* changes as the armature rotates.

(*a*) While the armature is making the first quarter of a revolution from the A position, the bars will move until bar *a* touches the + brush and bar *b* touches the – brush; and the electromotive force between the bars will grow from zero to the full value, E, of the direct electromotive force between the brushes.

---

*Note. The following discussion applies to multipolar machines also, but the statements are much simpler when limited to the bipolar machine.

(*b*) While the armature is making the second quarter of a revolution from the A position, the bars will move until they are again midway between the direct-current brushes; and the electromotive force between the bars will drop from the value E to zero.

(*c*) While the armature is making the third quarter of a revolution from the A position, the bars will move until bar *a* touches the – brush, and bar *b* touches the + brush; and the electromotive force between the bars, which must now be considered as negative, will grow from zero to the value E.

(*d*) While the armature is making the fourth quarter of a revolution from the A position, the bars will move until they are again midway between the direct-current brushes; and the electromotive force between the bars, which is still to be considered as negative, will drop from the value E to zero.

These successive changes of electromotive force, between the given pair *a b* of commutator bars, which occur during one complete revolution of the armature, are shown graphically in Fig. 260.

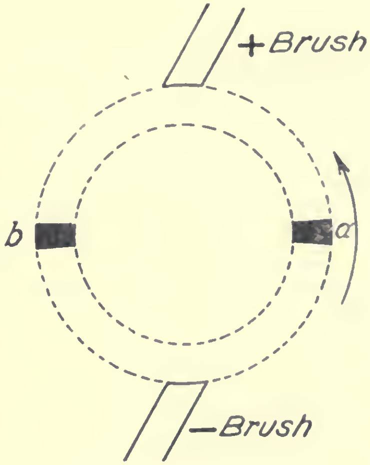


Fig. 259.

It is at once evident that the electromotive force between the bars *a* and *b* is an alternating electromotive force, and that this alternating electromotive force passes through a cycle of values during each revolution of the armature, so that its *frequency is equal to the revolutions per second of the armature* (for the case of a bipolar machine).

Furthermore, it is clear that the alternating electromotive force between a given pair of commutator bars *a b* on a direct-current dynamo may be utilized for the production of alternating current; or the direct-current dynamo may be made into an alternator by providing a pair of insulated metal collecting rings connected permanently to the bars *a* and *b* respectively, and which are kept in continuous connection with an outside circuit by means of an auxiliary pair of brushes, that is, brushes entirely separate and distinct from the direct-current brushes before mentioned.

A direct-current dynamo made into an alternator as above explained, but with its direct-current brushes and commutator kept intact, is called a **rotary converter**; and in this particular case, where two collecting rings, only, are provided, the machine is called a **single-phase rotary converter.** When the machine is provided, as explained below, with three collecting rings, four collecting rings, or six collecting rings, it is called a **polyphase rotary converter.**

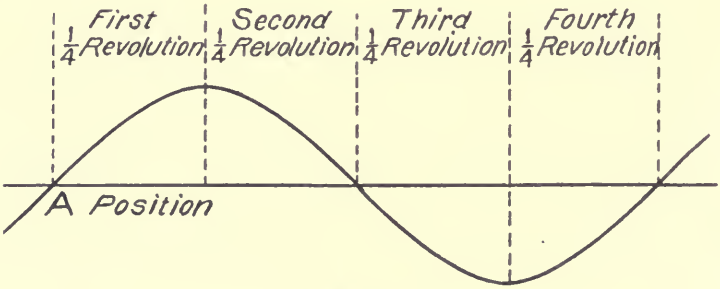


Fig. 260.

118. The Three-Ring Converter. Three equidistant commutator bars *a*, *b*, and *c* (Fig. 261) of a direct-current dynamo are connected to three collector rings. It is shown later in this discussion that the electromotive force between bars *a* and *b* is, in phase, 120° ahead of the electromotive force between bars *b* and *c*, and 240° ahead of the electromotive force between bars *c* and *a*. Three electromotive forces related in this way are called **three-phase electromotive forces**; and a direct-current dynamo provided with three slip-rings as specified, is called a **three-phase** or **three-ring rotary converter.**

119. The Four-Ring Converter. Four equidistant commutator bars *a*, *b*, *a'* and *b'* (Fig. 262) of a direct-current dynamo are connected to four collecting rings. Then the electromotive force between the rings *a* and *a'* is at its zero value when the electromotive force between rings b and b' is at its greatest value, or *vice versa.* Two electromotive forces related in this way are called **two-phase electromotive forces**; and a direct-current dynamo provided with four collecting rings as specified, is called a **two-phase** or, more accurately, a **four-ring rotary converter.**

120. The Six-Ring Converter. Six equidistant commutator bars a, b, c, a', b', c' (Fig. 263) of a direct-current dynamo, are connected to six slip-rings. Such a machine is called a **six-phase** or **six-ring rotary converter.** The electromotive force between the rings a and a' is, in phase, 120° ahead of the electromotive force between rings b and b', and 240° ahead of the electromotive force between rings c and c'. Three electromotive forces so related are called **three-phase electromotive forces**; and a six-ring rotary converter may, under certain conditions, be supplied with three-phase alternating currents.

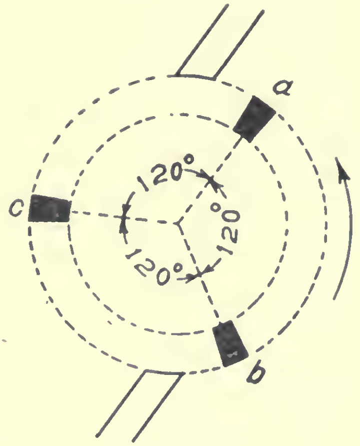


Fig. 261.

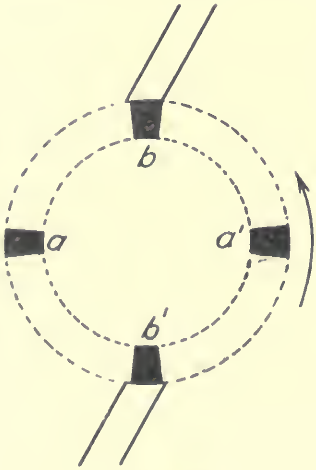


Fig. 262.

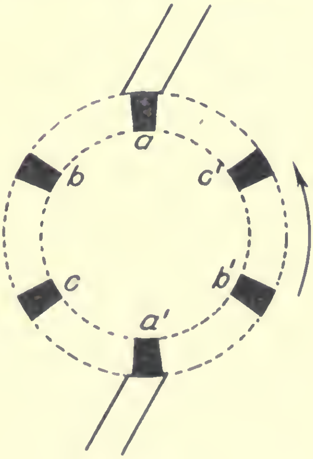


Fig. 263.

121. Multipolar Rotary Converters. The foregoing articles (117 to 120) refer, for the sake of simplicity, to a bipolar machine. In the case of a multipolar direct-current dynamo, having p field magnet poles, the connections of the n rings of an n-ring converter are as follows:

Ring No. 1 is connected to the $\frac{p}{2}$ equidistant commutator bars which, for a given position of the armature, are squarely opposite to the centers of, say, the north poles of the field magnet. Let d be the distance between the commutator bars to which ring No. 1 is connected. Ring No. 2 is connected to the $\frac{p}{2}$ equidistant commutator bars which are $\frac{1}{n}$ of d ahead of the bars connected to ring No. 1; ring No. 3 is connected to the $\frac{p}{2}$ equidistant commutator bars which are $\frac{2}{n}$ of d ahead of the bars connected to ring No. 1; and so on.

Example. A 6-pole direct-current dynamo with 72 commutator bars, to be made into a three-ring converter, would have ring No. 1 connected to commutator bars 1, 25, and 49; ring No. 2 connected to commutator bars 9, 33, and 57; and ring No. 3 connected to commutator bars 17, 41, and 65.

122. Electromotive Force Relations of the Rotary Converter. Let E be the value of the steady electromotive force between the direct-current brushes of a rotary converter; and let E_2, E_3, E_4, E_6, be the *effective values* of the alternating electromotive force between *adjacent* collecting rings of a 2-ring, 3-ring, 4-ring, and 6-ring rotary converter, respectively. It is desired to find the relationship between these various electromotive forces.

Relationship between E and E_2. The maximum value of the alternating electromotive force between the collecting rings of a 2-ring converter, occurs at the instant when the commutator bars to which the collecting rings are connected are in contact with the direct-current brushes, and this maximum value is, of course, equal to E. Therefore the effective value, E_2, of the alternating electromotive force between the slip-rings of a 2-ring converter is equal to $\frac{E}{\sqrt{2}}$. That is

$$E_2 = \frac{E}{\sqrt{2}} \qquad (39)$$

Relationship between E_2 and E_3. The discussion of the relationship between E_2 and E_3 will be carried out for a very special case, namely, where the armature has 18 conductors; and this special discussion will lead to a very simple geometrical construction which will easily give the relationship between E_2, E_3, E_4, and E_6, and will also show the phase relations of the various electromotive forces of a 3-ring, of a 4-ring, or of a 6-ring converter.

Fig. 264 represents a direct-current, ring-wound armature, having 18 conductors, each conductor, of course, representing a turn of wire. Consider the conductor *a*. This conductor has an alternating electromotive force induced in it as the armature rotates. Let this alternating electromotive force (effective value) be represented by the short line *a* in Fig. 265.

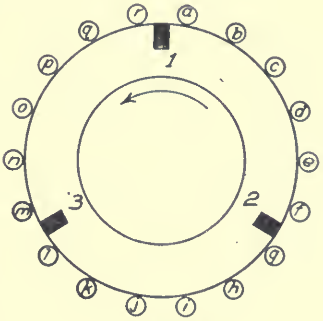


Fig. 264

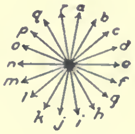


Fig. 265.

Consider the next following conductor *b*. The alternating electromotive force induced in this conductor has the same value as that induced in conductor *a*, but is *behind it in phase* by the angle $\frac{360°}{18} = 20°$, where 18 is the total number of armature conductors. Let the electromotive force induced in conductor *b* be represented by the short line *b* in Fig. 265.

Similarly, the short lines *c*, *d*, *e*, *f*, *g*, etc., in Fig. 265, represent the alternating electromotive forces (effective values) induced in the conductors *c*, *d*, *e*, *f*, *g*, etc.

Consider first the 2-ring converter. Suppose that its slip-ring No. 1 is connected to the commutator bar which is between conductors *r* and *a*, as shown in Fig. 264; then its other slip-ring will be connected to the bar which is between conductors *i* and *j*, and the alternating electromotive force E_2 between these two slip-rings will be the vector sum of the electromotive forces *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, and *i* (Fig. 265), as shown in Fig. 266. That is, E_2

(effective value) is represented by the diameter of the polygon (circle) in Fig. 266.

Consider now the 3-ring converter. Suppose its three rings are connected as shown by the numbers 1, 2, and 3 in Fig. 264. Then the electromotive force E'_3, between rings 1 and 2 is the vector sum of the electromotive forces *a*, *b*, *c*, *d*, *e*, and *f*, as shown in Fig. 266; the electromotive force E''_3, between rings 2 and 3, is the vector sum of the electromotive forces *g*, *h*, *i*, *j*, *k*, and *l*, as shown in Fig. 266, and the electromotive force E'''_3, between rings 3 and 1, is the vector sum of the electromotive forces *m*, *n*, *o*, *p*, *q*, and *r*, as shown in Fig. 266.

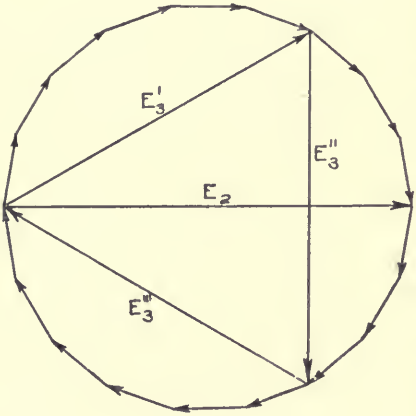


Fig. 266.

Therefore, the effective value of the electromotive force E_2 between the two rings of a 2-ring converter, being represented by the diameter of a circle, the effective value of the electromotive force E_3, between any two rings of a 3-ring converter is represented by a 120° chord of the same circle. Therefore:

$$E_3 = \frac{\sqrt{3}}{2} . E_2;$$

or, using the value of E_2 from equation 39, we have:

$$E_3 = \frac{\sqrt{3}}{2} . \frac{E}{\sqrt{2}} = 0.612\ E. \qquad \textbf{(40)}$$

It is to be noted that in order to make a direct-current machine into a 3-, 4-, or 6-ring converter, the number of armature conductors must be divisible by the number of rings. Therefore, the armature shown in Fig. 264 is not suitable for a 4-ring converter, although it is suitable for a 6-ring converter.

General Statement of Relationship between E_2, E_3, E_4, and E_6. The foregoing discussion shows that if the effective value of

E_2 is represented by the diameter of a circle, then the effective value of E_3 is represented by a 120° chord, the effective value of E_4 is represented by a 90° chord, and the effective value of E_6 is represented by a 60° chord of the same circle. This is shown in Figs. 266, 267, and 268.

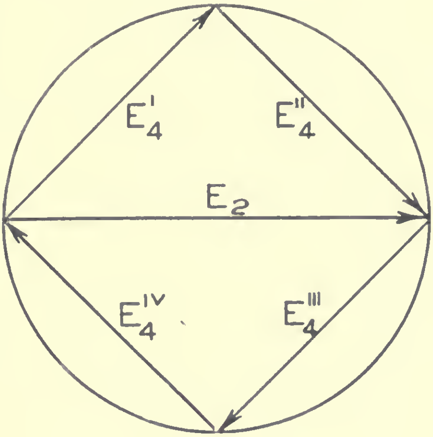


Fig. 267.

From Fig. 267, we have:

$$E_4 = \frac{E_2}{\sqrt{2}};$$

or, substituting the value of E_2 from equation 39, we have:

$$E_4 = \frac{1}{\sqrt{2}} \times \frac{E}{\sqrt{2}} = \frac{E}{2}. \quad (41)$$

From Fig. 268 we have:

$$E_6 = \frac{1}{2} E_2;$$

or, substituting the value of E_2 from equation 39, we have:

$$E_6 = \frac{1}{2} \times \frac{E}{\sqrt{2}} = 0.354E. \quad (42)$$

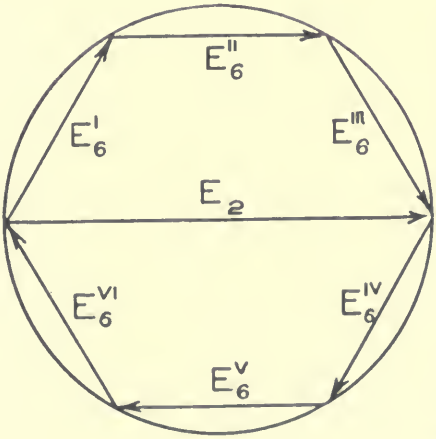


Fig. 268.

Summary of Electromotive Force Relations of the Rotary Converter. Let E be the electromotive force between the direct-current brushes of a rotary converter; then,

$$\left.\begin{aligned} E_2 &= 0.707\ E \\ E_3 &= 0.612\ E \\ E_4 &= 0.500\ E \\ E_6 &= 0.354\ E \end{aligned}\right\} \quad (43)$$

in which E_2, E_3, E_4, and E_6, are the effective values of the alternating electromotive force between adjacent collecting rings on a 2-ring, 3-ring, 4-ring, and 6-ring converter respectively, and E is the steady value of the electromotive force between the direct-current brushes in each case.

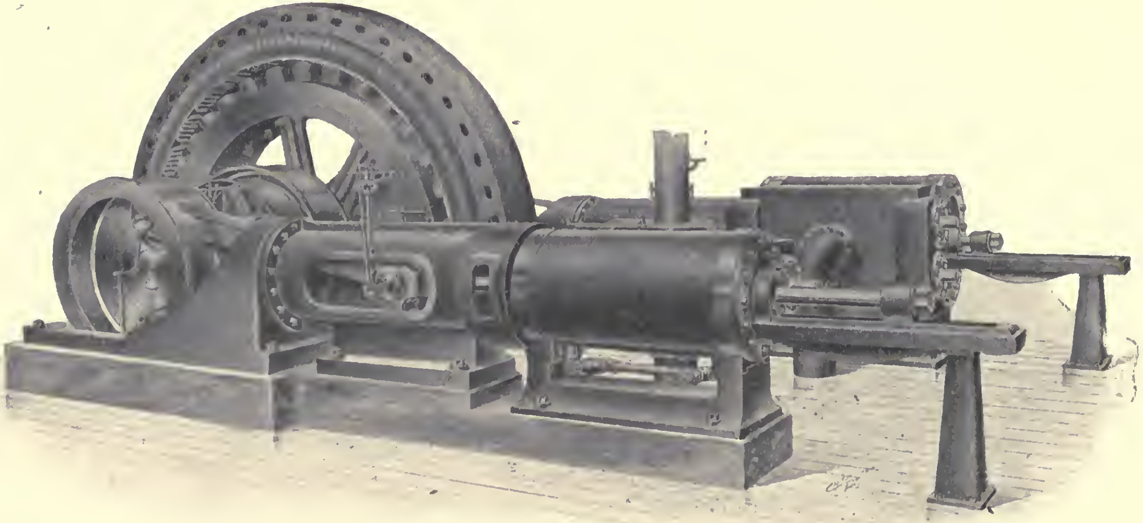
Examples. A rotary converter is to deliver direct current at 500 volts.

(*a*) It must be supplied with single-phase alternating current at 353.5 volts, effective, if it is a 2-ring converter.

(*b*) It must be supplied with three-phase currents at 306 volts effective between each pair of the three supply mains, if the converter is a 3-ring converter.

(*c*) It must be supplied with two-phase currents over four-wire supply mains with 250 volts effective between mains connected to adjacent collector rings, or 353.5 volts effective between mains connected to opposite collector rings, if the converter is a 4-ring converter.

(*d*) It must be supplied with six-phase currents over six-wire supply mains, with 177 volts effective between the mains connected to adjacent collector rings; or with 306 volts effective between the mains connected to rings 1 and 3; or with 353.5 volts effective between the mains connected to opposite collector rings.



CROSS-COMPOUND ENGINE DIRECT-CONNECTED TO ALTERNATING-CURRENT GENERATOR.

Buckeye Engine Company

ALTERNATING CURRENT MACHINERY.

PART V.

123. Modification of Theoretical Voltage Ratios in Actual Machines. The theoretical ratios of alternating to direct-current voltage are not always found to hold good in practice. This is owing to a variety of causes, chief among which are: the deviation of the generator voltage from a sine wave, the voltage drop in the armature windings, the position of the direct-current brushes on the commutator, and the degree of field excitation.

As the direct-current voltage at the commutator brushes, neglecting the resistance drop RI in the converter, is equal to the maximum instantaneous voltage between opposite collector rings, a flat-top wave gives a higher ratio (*i.e.*, lower direct-current voltage), and a peaked wave a lower ratio (*i.e.*, higher direct-current voltage), for the same impressed alternating-current voltage. Moreover, the shape of the electromotive force wave impressed by the generator upon the converter, is modified by the form of the counter electromotive force wave of the converter. Hence, a short pole arc of the converter, producing a peaked wave of counter electromotive force, tends to lower the direct-current voltage, and a long pole arc tends to raise the direct-current voltage, for the same impressed alternating voltage.

A displacement of the brushes from the neutral point decreases the direct-current voltage for a given alternating-current voltage, the variation in extreme cases amounting to several per cent.

Over-excitation of the field magnet may increase the direct-current voltage one or two per cent; while with under-excitation, *i.e.*, with lagging current, the direct-current voltage may be decreased one or two per cent for a given alternating current voltage.

Under average conditions of full-load operation, the standard types of converters have ratios *alternating-current voltage ÷ direct-current voltage*, approximately as given below:

TABLE VII.

Voltage Ratios of Rotary Converters.

Percentage pole arc :		50 per cent.	67 per cent.	74 per cent.	80 per cent.
Three-phase,	550-volt,	67	63	62	61.5
	250-volt,	67.5	63.5	62.5	62
	125-volt,	68	63.8	63	62.5
Two-phase,	550-volt,	78	73.5	72.5	72
	250-volt,	79	74	73	72.5
	125-volt,	79.5	74.5	73.5	73

In the normal operation of the rotary converter—namely, when furnishing direct current, the drop in the armature reduces the direct-current voltage. When run as an inverted converter, *i.e.*, when delivering alternating current, direct current being fed to the brushes, the drop is on the alternating side; consequently the voltage ratio of a converter is lower when it is run inverted.

For preliminary calculations where the data of operation are not known, the following voltage ratios may be used with most standard converters:

For two-phase, 74;
For three-phase, 64.5.

In operating rotary converters, it is customary to make allowance for the departure of the actual voltage ratio from the normal ratio. The amount of the allowance to be made cannot always be predetermined; but any ordinary departure from the theoretical voltage may be easily compensated for by using transformers provided with taps on the secondary windings which will permit a voltage change of about 5 per cent.

124. Current Relations of the Rotary Converter. The rotary converter, as ordinarily used to convert alternating current to direct current, behaves as a synchronous motor in so far as its intake of alternating current or currents is concerned. In the case of the synchronous motor with a given belt load, the intake of alternating current varies with the degree of field excitation, the intake of current being a minimum for a certain field excitation, and the power factor nearly unity (see article 74). In the case of the rotary converter, also, the intake of alternating current or currents is a minimum, and its power factor is unity for a certain field excitation, the direct-current output of power being given. Under these conditions there is a definite relation between the direct-current I delivered by the converter, and the *effective* value of the alternating current flowing in at each collecting ring. In fact,

$$\left.\begin{aligned} I_2 &= 1.414\ I \\ I_3 &= 0.943\ I \\ I_4 &= 0.707\ I \\ I_6 &= 0.471\ I \end{aligned}\right\} \qquad \textbf{(44)}$$

in which I_2, I_3, I_4, and I_6 are the effective values of the alternating current entering at each collector ring of a 2-ring, 3-ring, 4-ring, or 6-ring converter, respectively; and I is the direct current delivered by the converter. These equations 44 are based on the assumption that the converter has unity power factor as above pointed out, and that the intake of power is equal to the output of power, *i.e.*, the losses of power in the machine are ignored.

The method of deriving equations 44 will be sufficiently indicated by deriving the first two, namely, the equations for I_2 and I_3.

Derivation of the Equation for I_2. The direct-current output of power from the converter is EI, E being the electromotive force between the direct-current brushes, and I being the direct current delivered. The intake of power is E_2I_2 × power factor; but since the power factor is supposed to be unity, the intake of power is simply E_2I_2. Therefore, ignoring losses of power, we have:

$$E_2I_2 = EI$$

But $E_2 = 0.707\ E$, by the first of equations 43, so that $E_2I_2 = 0.707E \times I_2 = EI$.

Hence $$0.707\ I_2 = I;$$
or, $$I_2 = 1.414\ I.$$

Derivation of the Equation for I_3. The direct-current output of power is EI, and the intake of power is $\sqrt{3}\ E_3I_3$, the power factor being unity; that is, the power delivered by three-phase supply mains is equal to $\sqrt{3}$ times the voltage between mains times the current in each main, as explained in article 49. Therefore, ignoring power losses in the machine, we have:

$$\sqrt{3}\, E_3 I_3 = EI.$$

But $E_3 = 0.612\ E$, according to the second of equations 43, so

$$\text{that } \sqrt{3}\ E_3 I_3 = \sqrt{3} \times 0.612 \times EI_3 = EI.$$

Hence
$$\sqrt{3} \times 0.612\ I_3 = I;$$
or,
$$I_3 = 0.943\ I.$$

Examples. A rotary converter delivers 500 amperes of direct current, the field excitation being adjusted so that the intake of alternating current may be a minimum.

(*a*) If this converter is a 2-ring converter, it must be supplied with 707 amperes of alternating current from single-phase mains.

(*b*) If this converter is a 3-ring converter, it must be supplied with three-phase currents from three-wire mains, with 471.5 amperes effective in each main.

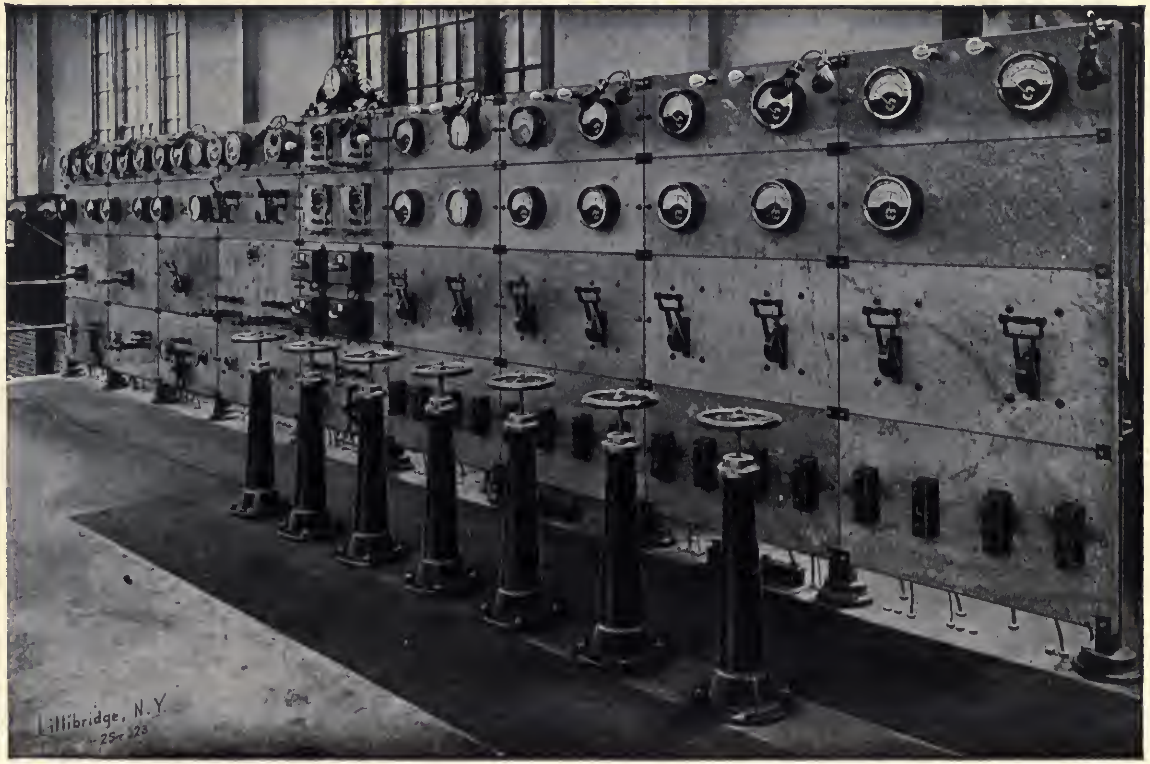
(*c*) If this converter is a 4-ring converter, it must be supplied with two-phase currents from four-wire supply mains, with 353.5 amperes effective in each main.

(*d*) If this converter is a 6-ring converter, it must be supplied with six-phase currents from six-wire mains, with 235.5 amperes effective in each main.

125. Possible Uses of the Rotary Converter. The uses of the rotary converter are as follows:

(*a*) *Direct-Current Generator or Motor.* The rotary converter may be used as a direct-current generator or motor, in which cases the collector rings are not used, but the machine must be provided with a pulley.

(*b*) *Alternating-Current Generator or Synchronous Motor.* The machine may be driven by belt and used to deliver alternating currents from its collector rings as an ordinary alternator; or the machine may be supplied through its collector rings with alternating currents, and may be driven as an ordinary synchronous motor delivering mechanical power to drive machinery. In either case the direct current for exciting the field magnet may be taken from the commutator of the machine, or from a separate direct-current dynamo (exciter).



A TYPICAL SMALL S.K.C. SWITCHBOARD.

Stanley Electric Manufacturing Co.

(*c*) *Double-Current Generator.* The rotary converter may be driven by belt, and used to deliver both direct current and alternating current from commutator and collector rings, respectively. When so used, the machine is called a **double-current generator.**

(*d*) *Regular Rotary Converter.* The machine may be driven as a synchronous motor taking alternating current from supply mains, and delivering, not mechanical power, but electrical power in the form of direct current from its commutator. When so used, the machine is called a **rotary converter.** This is the most frequent use of the machine. The rotary converter does not require a pulley.

(*e*) *Inverted Rotary Converter.* The machine may be driven as a direct-current motor taking current from direct-current supply mains through its commutator, and delivering, not mechanical power, but electrical power in the form of alternating currents from its collector rings. When so used, the machine is called an **inverted rotary converter**; it does not require a pulley.

126. Behavior of the Regular Rotary Converter. When used to convert alternating current to direct current, the rotary converter is a synchronous motor in so far as its relations to the alternating-current supply are concerned; and the machine exhibits all of the peculiarities of the synchronous motor, as described in article 74. Thus, with under-excited field magnet, the rotary converter takes an unduly large amount of alternating current from the supply mains at a low power factor. As the field excitation is increased, the intake of alternating current decreases (for given output of direct-current power), and the power factor increases. For a certain degree of field excitation the power factor is nearly unity, and the alternating current or currents delivered to the machine are in phase with the alternating electromotive forces between the supply mains. When the field magnet is over-excited, the alternating currents supplied to the converter are ahead of the alternating electromotive forces in phase, as explained in article 74, and the power factor is less than unity.

The rotary converter may be started exactly as an ordinary synchronous motor, as described in article 71; or it may be started by supplying direct current to the commutator end of the machine, and starting the converter as a shunt-wound direct-current motor, the alternating-current main-switch being open. This method is the one generally used where direct current is available for starting purposes. In some cases the direct current is obtained from another converter already in operation, or from a small storage battery which may be at hand. Sometimes a small motor-generator set, consisting of an induction motor coupled to a direct-current generator, is installed to supply current for the starting of one or more converters in a station.

In the case of the latter method of starting, the fields should be fully excited by closing the field switch first, and there should be a resistance in series with the armature when the motor switch is closed. Failure to excite the field may cause the converter to increase its speed to a dangerous extent, just as in the case of a direct-current shunt motor with excessively weak field, for in starting the converter from the direct-current end, it is not running as a synchronous motor but as a simple shunt direct-current motor.

The operation of starting is then as follows:

(1) See that the alternating-current main switch is open.

(2) Close the field switch.

(3) Leave the starting resistance in circuit with the armature, and then close the main switch.

(4) When normal speed is reached, cut out the starting rheostat, and vary the field strength until the synchronizing device shows that the converter is in synchronism with the generator.

(5) Close the main alternating-current switch when the synchronizing device shows that the rotary converter is in step with the alternating-current supply.

If the converter is furnished with a shunt winding only, adjust the field to give minimum alternating-current input.

If the converter has a series winding also, the shunt field should be adjusted to give at no load the direct-current no-load voltage at which it is rated.

When a rotary converter is started as a direct-current motor, it is easy to bring the machine into operation with a particular direct-current brush or set of brushes *positive*. When, however, the machine is self-started as an alternating-current motor, a particular direct-current brush or set of brushes may be positive or negative according to the direction of the last pulse of alternating current just before the machine jumps into synchronism. Therefore, when several rotary converters are to supply direct current to common bus bars, special care must be taken to see that the *polarity* of a given machine is correct before it is connected to the bus bars.

The armature of a belted dynamo or motor is always caused by the belt to shift slowly to and fro endwise in its bearings, thus entirely obviating the uneven wearing away of the commutator in grooves where the brushes rub. The rotary converter, however, tends to run without end-play, and some special end-play device is necessary. The simplest is an electromagnet mounted opposite to the end of the rotary-converter shaft. This electromagnet is excited about ten times per minute, and on each occasion gives an endwise pull on the shaft, causing the desired endwise movement of the latter. A mechanical end-play device now much used consists of a steel ball which plays between the flat end of the shaft and an inclined runway in a steel plate mounted opposite to

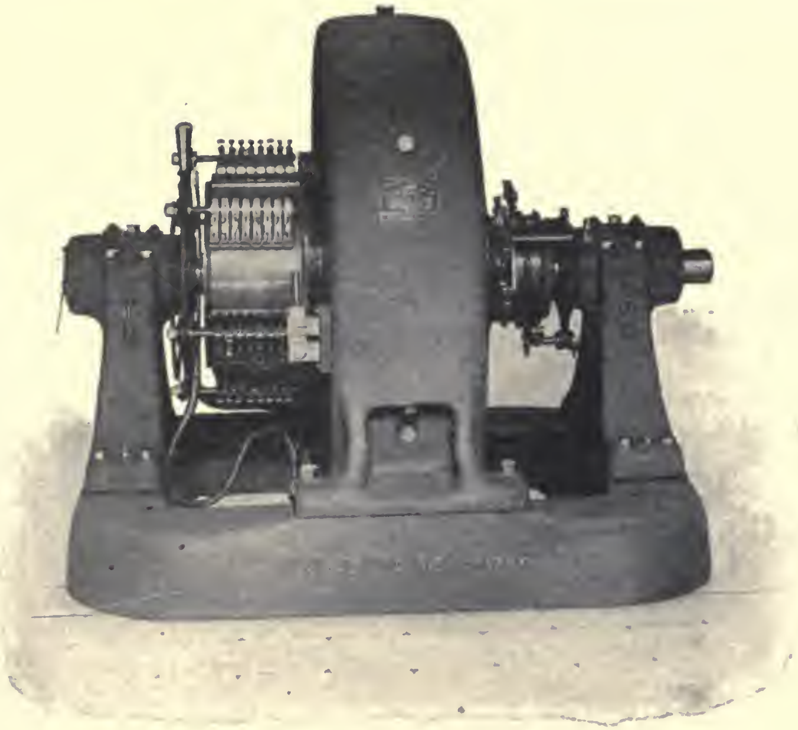


Fig. 263.

the end of the shaft, and backed by a spring that allows the steel plate to yield more or less when the shaft strikes it in its to-and-fro motion.

Fig. 269 shows a 300-kilowatt, three-phase (3-ring) rotary converter built by the General Electric Company. It has a 6-pole field magnet and six sets of direct-current brushes, each set having eight single brushes. Its rated speed is 500 revolutions per minute, which with a six-pole field, gives a frequency of 25 cycles per second. The three collector rings are mounted on the armature shaft on the end opposite to the commutator. It can be seen from the figure that the commutator is larger in comparison with the size of the machine than is usual in an ordinary direct-current generator. Each collector ring has three brushes bearing upon it

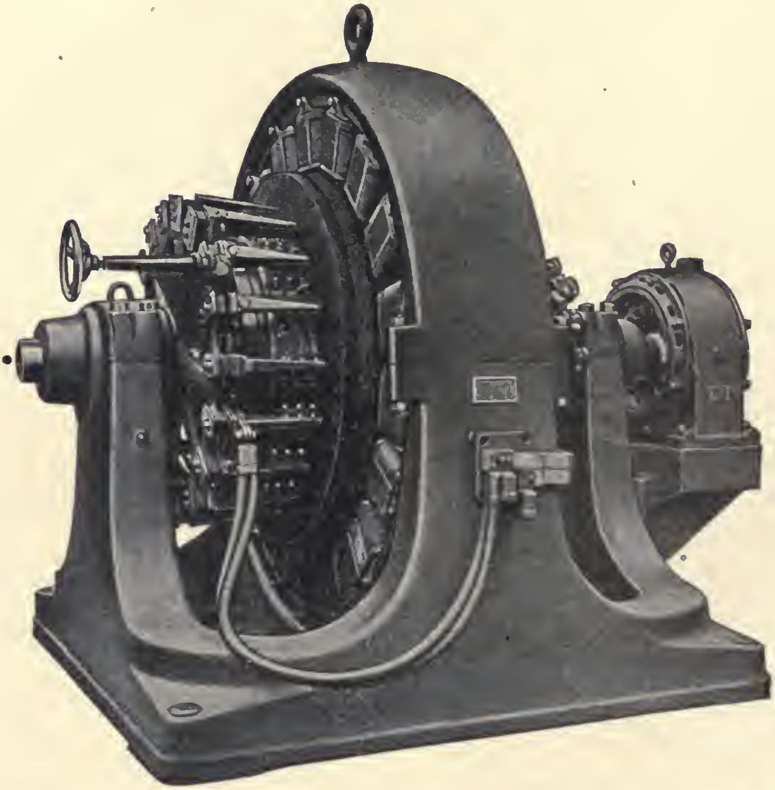


Fig. 270.

in order to permit of the delivery to the machine of the very large alternating currents from the supply mains. The use of three brushes on each collector ring is preferable to the use of one broad brush, inasmuch as it is desirable to make the rings narrow to save space. This machine is rated at 550 volts between its direct-current brushes, so that the full-load direct-current output is 300,000 watts divided by 550 volts, or 546 amperes. Therefore, on the assumption of unity power factor and 100 per cent efficiency, as explained in article 124, the alternating current entering at each collector ring is 546 amperes × 0.943 = 515 amperes effective; and the effective voltage between collector rings is 550 volts × 0.612* = 336 volts. The alternating-current power supplied to the machine is:

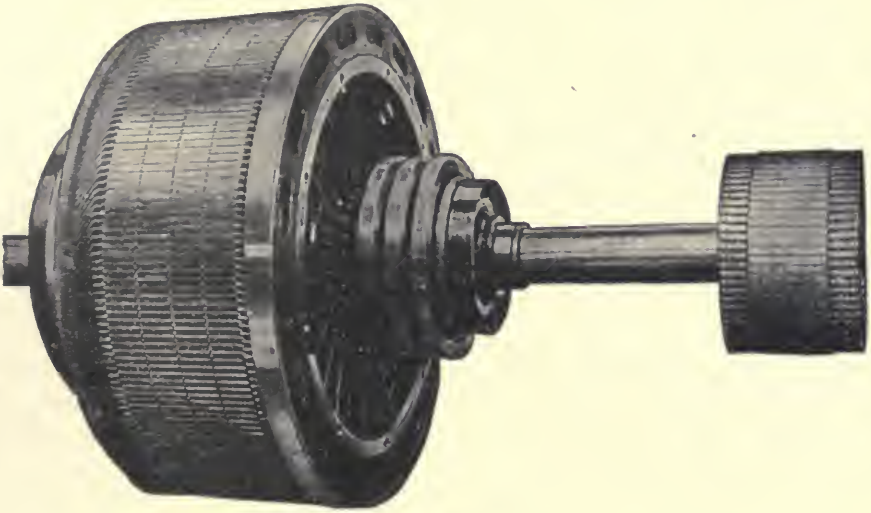


Fig. 271.

$$\sqrt{3} \times 336 \text{ volts} \times 515 \text{ amperes} = 300{,}000 \text{ watts.}$$

Fig. 270 shows a 500-kilowatt three-phase rotary converter manufactured by the Westinghouse Company. It is provided with an induction motor for separate starting, as described in article 71. The armature of the rotary converter and the "squirrel-cage" rotor of the induction motor are shown in Fig. 271. The field of the rotary converter has 18 poles, and the speed of the machine is 400 revolutions per minute, thus giving a frequency of 60 cycles per second (7,200 alternations per minute). In Fig. 271 the radial connecting wires from the armature winding to the collector rings are visible at the end of the armature next to the collector rings. There are 27 of these connectors, each ring being connected to 9 ($= \frac{18}{2}$) equidistant points of the armature winding.

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* See equation 40.

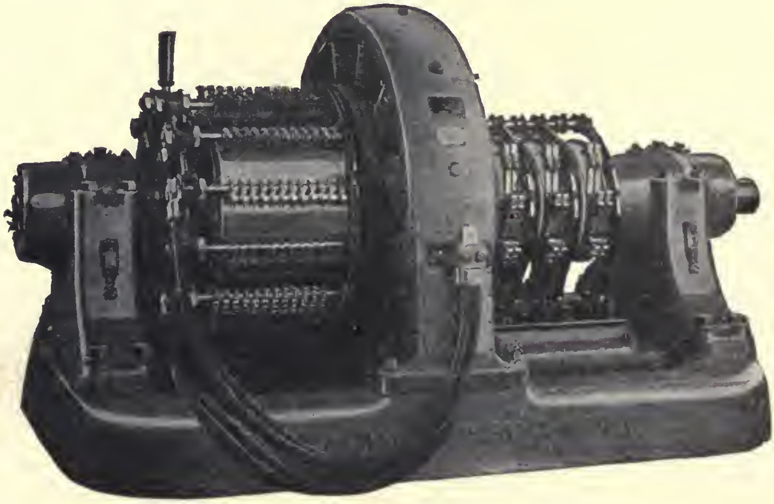


Fig. 272.

Fig. 272 shows a three-phase rotary converter manufactured by the General Electric Company. The characteristic features which distinguish the rotary converter from the direct-current generator are here especially prominent—namely, the large commutator and great brush contact area, the comparatively large collector rings, and the relatively small magnetic system.

127. Hunting of the Rotary Converter. A rotary converter (regular), being a synchronous motor in relation to its alternating-current supply, has a tendency to hunt, as explained in article 72. A rotary converter, however, having no pulley and not being mechanically connected to machinery, is much more sensitive in responding to the pulsations of an engine or to other causes of hunting than is a synchronous motor delivering mechanical power.

The hunting oscillations of a synchronous motor are always due to external disturbances, that is, to disturbances originating outside of the alternating-current generator, the line, and the synchronous motor.

A sudden change of load on the synchronous motor, for example, is followed by a series of oscillations. Whether or not the oscillations due to a certain change of load give rise to trouble, depends largely upon the resistance and reactance of the transmission line, and upon the frequency. The greater the resistance and reactance of the transmission line, the greater the trouble from hunting; and at high frequencies the trouble from hunting is much greater than at low frequencies. Thus a 25-cycle rotary converter gives no serious trouble from hunting if the line resistance and reactance are not excessively high, whereas a 60-cycle rotary converter is more likely to give trouble unless special provision is made to diminish hunting as explained below.

A periodic variation in the speed of the engine driving the alternator from which a rotary is supplied with alternating current, produces very troublesome hunting when this variation of speed is in rhythm with the hunting oscillations. This class of hunting is obviated by increasing the fly-wheel capacity of the engine, or by changing the resistance or reactance of the transmission lines. The latter method changes the rhythm of the hunting oscillations and thereby does away with the coincidence of rhythm, which is the chief cause of excessive hunting oscillations due to engine pulsations.

The hunting oscillations, once started, usually reach their maximum under given conditions in a few minutes' time, so that serious trouble due to hunting, such as the dropping out of step of the rotary, or excessive sparking at the commutator, usually occurs soon after the hunting begins.

Hunting is more troublesome when the field of the rotary converter is over-excited so as to take leading currents, than when the excitation is such as to give either unity power factor or lagging currents.

The amount of hunting or pulsation of a rotary converter is approximately the same at all loads, from no-load to over-load.

Hunting is more troublesome when several rotaries are supplied from an alternating-current generator, than when a single rotary converter is supplied, unless there are short lengths of alternating-current mains between them, or unless the converters supply direct current in parallel to the same direct-current mains.

Hunting, whether due to engine pulsations, or to momentary outside disturbance, such as sudden change of load or momentary short circuit, is greatly reduced by the use of massive copper bridges or frames extending partly over the pole faces, as shown in Figs. 151 and 177. A more effective arrangement is shown in Fig. 273. A number of holes or channels are provided in each pole tip. In these holes or channels heavy copper conductors A and B are placed, and these conductors are short-circuited by being connected at the ends by the bars C C. These copper frames diminish hunting oscillations by means of the following action:

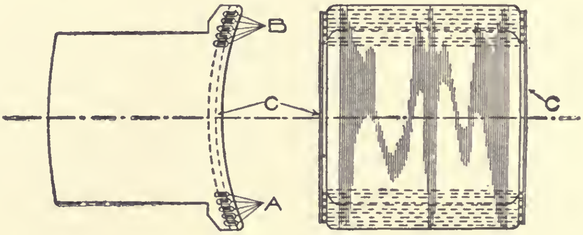


Fig. 273.

> When a machine is hunting, the magnetic flux from pole-face to armature core is shifted forwards and backwards over the pole-face, and this shifting flux induces electromotive forces in the copper frames, these electromotive forces produce currents which oppose the shifting of the flux, and thereby oppose the hunting oscillations.

A rotary converter having solid cast-steel pole pieces has little or no tendency to hunt. The action of the solid poles is the same as the action of the massive copper conductors shown in Fig. 273. The use of solid poles, however, leads to excessive eddy-current losses; hence solid poles are not considered desirable.

128. Inverted Rotaries. When a rotary converter is used to convert a direct current into an alternating current, taking direct current in at the commutator and delivering alternating current at the collector rings, it is called an **inverted rotary converter.** While the rotary converter is generally used to convert alternating current into direct current, it sometimes happens that inverted converters are desirable. For example, in a low-tension direct-current system, a district remote from the central station may be supplied with current by converting direct current to alternating current at the station (by means of inverted rotaries); then, by step-up transformers, raising the voltage to a high value, and transmitting it as high-tension alternating current; and finally, at the distant point, reconverting it (using step-down transformers) to direct current. Again, in a station containing direct-current generators for short-distance supply, and alternators for long-distance supply, the converter may be used as the connecting link to shift the load from the direct to the alternating generators, or conversely. The machine which is used for shifting the load in this way is caused to operate as a regular rotary or as an inverted rotary according to the demand for direct current or alternating current.

The behavior of an inverted rotary converter is different in many respects from the performance of the same machine when used as a regular rotary converter. When converting from alternating current to direct current, the speed of the converter is rigidly fixed by the frequency of the alternating current supplied to it, and cannot be varied by altering its field excitation; this would merely change the phase difference between the alternating electromotive force and current supplied to the machine, and hence the power factor, as in the case of the synchronous motor. When converting from direct current to alternating current, however, the speed of the converter, as in a direct-current motor, will be proportional to the applied direct-current voltage, and will also depend upon the field excitation. The effect of weakening the field is to increase the speed, and the effect of strengthening the field is to decrease the speed. It is evident, therefore, that there should be little or no series field winding provided on an inverted rotary converter, as it will change in speed under load and deliver alternating currents at a variable frequency. If the field becomes greatly weakened, an inverted rotary converter may reach a dangerously high speed before the attendant has time to prevent it, and the armature of the machine may be torn to pieces by the excessively large centrifugal forces.

Changing the field excitation of an inverted rotary converter will not change the voltage of the alternating current, because the ratio of transformation in a given converter is fixed; changing the field strength merely causes a change in the speed of the rotary.

The voltage of the alternating current may be changed by changing the voltage of the applied direct current, or it may be varied by using alternating-current-potential regulators as described later.

An inverted rotary being an alternating-current generator, the field strength depends upon the intensity and phase relation of the alternating current; thus a lagging current reduces the field strength, and hence increases the speed and frequency; whereas a leading current increases the field strength, and thus decreases the speed and frequency. Again, if the alternating-current side of an inverted rotary converter delivers large lagging currents to inductive receiving circuits, the demagnetizing action of the lagging currents on the field may result in a dangerously high speed. In operating inverted rotary converters, therefore, especially when they are liable to be overloaded on the alternating-current side, as in the starting of synchronous or induction motors supplied from the inverted rotary, great care should be taken to see that the field excitation is always great enough to prevent excessive speeds. When used for the above purpose, special speed-limiting devices should be used.

A method used by the Westinghouse Company to prevent this tendency of the inverted rotary converter to race, is as follows:

> The converter is separately excited by a small direct-current generator mechanically connected to, and driven by, it. The speed of the exciter will therefore change with every change in the speed of the inverted rotary. The magnetic circuit (magnet cores, yoke, etc.,) and magnet coils of the exciter are so designed that its armature can generate normal voltage when the machine is being worked at a point considerably below the "knee" of the saturation curve. Any increase in the speed of the exciter will therefore cause a great increase in its voltage. If then the speed of the inverted rotary converter increases, the voltage of the exciter immediately increases and strengthens the field of the converter, thus checking its tendency to race.

The same result is attained by the General Electric Company, but in a different manner, as follows:

> A kind of centrifugal governor is attached to the shaft of the inverted rotary and revolves with it. If the speed of the rotary converter increases above a certain value, the governor acts, and closes an electric circuit which automatically throws off the power supplied to the rotary.

Fig. 274 shows a 75-kilowatt Westinghouse rotary converter intended to be operated as an inverted rotary. It is provided with a small shunt-wound direct-current exciter, whose armature is mounted on the main shaft of the converter, while its field magnet frame is bolted to an extension of the main casting of the converter, as shown in the figure. The tendency of the inverted converter to race is checked by the action of the specially designed exciter as explained above.

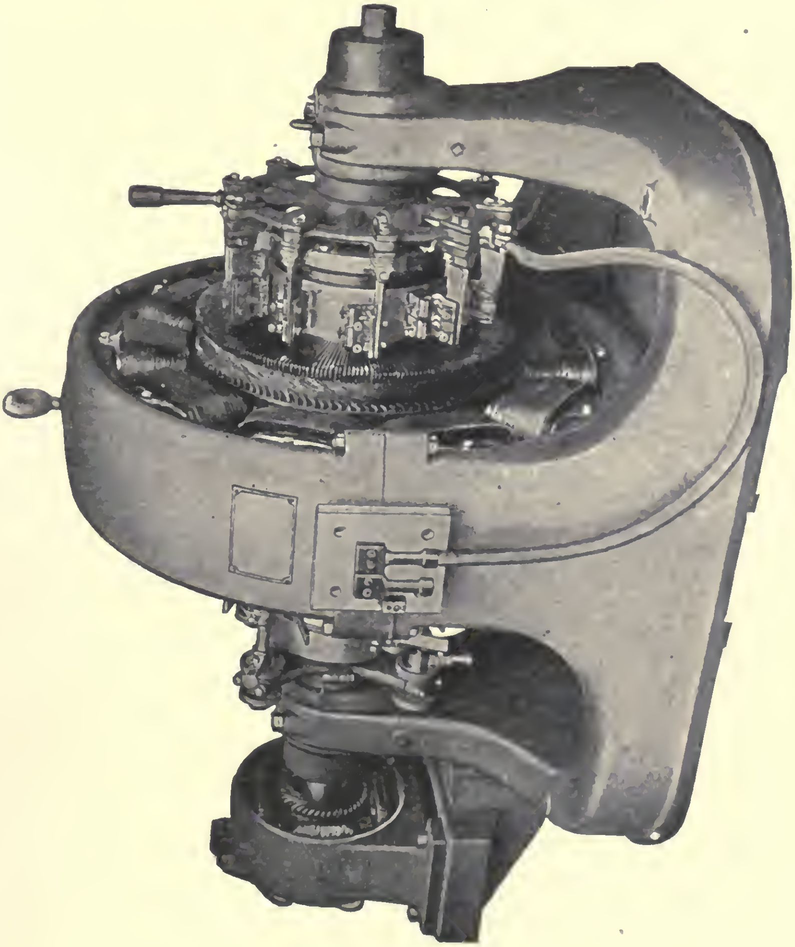


Fig. 274.

129. Control of Direct-Current Voltage of a Rotary Converter. The relations between the alternating-current voltages supplied to a rotary converter and the direct-current voltage of the machine, as explained in article 122, and as expressed in equations 43, apply to the case in which the field excitation of the rotary converter is such that the alternating currents delivered to the machine are in phase with the applied alternating-current voltages; that is, these relations apply to the case in which the power factor of the machine is unity. The direct-current voltage of a rotary converter may be slightly greater or less than the ideal value given in equations 43, as explained in article 123.

Control of the direct-current voltage of a rotary converter may be accomplished through a considerable range by varying the values of the supplied alternating-current voltage by means of voltage regulators (treated later), or by providing a series of taps on the secondaries of the step-down transformers that supply alternating current to the rotary converter so that the number of secondary turns in these transformers, and therefore the value of the secondary voltage, may be varied at will.

Another method of direct-current voltage control is as follows:

As pointed out in article 74, the field excitation of a *synchronous motor* may be varied through quite a range above or below that corresponding to unity power factor, the machine taking leading currents when its field is over-excited, and lagging currents when its field is under-excited. This is especially the case when the synchronous motor has considerable armature inductance, and when the transmission line also has considerable inductance. This remark applies to the *rotary converter* also; and, *when the transmission line has considerable reactance*, the alternating-current voltages between the collector rings of a rotary converter and the direct-current voltage between its direct-current brushes, vary with the field excitation of the converter.

Where there is both inductance and resistance drop in the feeders, and a considerable variation in the alternating voltage supply, the converter, if provided with series field winding, can be made to regulate automatically for constant direct-current voltage within reasonable limits, as explained below.

As the ratio of the alternating to the direct-current voltage of a converter is nearly constant, the impressed alternating voltage must be varied in order to vary the direct-current voltage. This can be done by taking advantage of the fact that an alternating current passing over an inductive circuit will decrease in voltage if lagging in phase behind its electromotive force, and will increase in voltage if leading. Just as in the case of a synchronous motor, a certain field excitation in any converter will give a minimum armature current. If the excitation be decreased, the armature current will be increased but will be lagging. By providing, therefore, sufficient reactance in the alternating-current circuit connecting a converter with its source of power, the alternating-current voltage at the converter terminals may be varied by means of the field excitation of the converter, and without altering the generator voltage.

When it is desired to control the direct-current voltage of a rotary converter independently of the voltage of the alternating-current generator that supplies the alternating currents, the transmission line is frequently given an artificial reactance by connecting inductance (reactance) coils in series with the alternating-current supply mains. Thus the alternating currents delivered to the converter are caused to flow through these reactance coils. When, therefore, a rotary converter has a compound field winding (series and shunt), as described below, the use of reactance coils in the supply mains is necessary if the transmission lines do not of themselves have sufficient reactance.

130. Field Excitation of Rotary Converters. Various methods are employed for exciting the field magnet of rotary converters, as follows:

(*a*) *Field Excitation by Armature Reaction.* When an alternating-current generator delivers leading current to a receiving circuit, the magnetizing action of the armature currents tends to strengthen the field magnet poles, as explained in article 43. If an alternating-current generator were always used to deliver leading currents, it would be possible to depend upon the magnetizing action of the armature currents entirely for exciting the field magnet, without using any direct current whatever in the field windings; in fact, the field windings could be dispensed with altogether.

When a synchronous motor (or rotary converter) takes lagging currents from alternating-current supply mains, the magnetizing action of these currents in the motor armature is to strengthen the field magnetism of the motor (or rotary converter). This action alone may be utilized for exciting the field magnet of a synchronous motor (or rotary converter), and rotary converters have been designed and commercially operated with this mode of field excitation.

(*b*) *Self-excitation of the Field of Rotary Converters by Direct-Current Taken from the Commutator of the Machine.* The usual method of exciting the field of a rotary converter is by means of direct current taken from the commutator of the machine itself. There are three schemes for carrying out this method of field excitation, exactly as in the case of ordinary direct-current generators, as follows:

1. *Series Excitation.* This scheme, in which the entire direct-current output flows through the field winding (coarse wire), gives a field excitation which is zero when the direct-current output is zero, and which rises to full rated excitation when full-load output of direct current is reached. This scheme of field excitation is not suitable for rotary converters, inasmuch as a rotary converter should have an approximately constant field excitation, or a field excitation which changes through a comparatively narrow range only.

2. *Shunt Excitation.* In this scheme the field winding is made of comparatively fine wire. Its resistance, therefore, is comparatively high, and it is connected directly between the direct-current brushes with an adjustable field rheostat in its circuit, exactly as in the ordinary shunt-wound direct-current dynamo. This scheme gives an approximately constant field excitation, and it is much used in rotary converters. The variation of field excitation for the purpose of controlling the power factor of the converter is accomplished by means of the adjustable field rheostat.

3. *Compound Excitation.* The combination of series and shunt excitation is frequently used in rotary converters so as to provide for slightly increasing field excitation (by means of the series winding) with increasing direct-current output. This scheme of field excitation is, however, more limited when applied to a rotary converter than when applied to an ordinary direct-current dynamo, for the reason that too great an increase of field excitation

in a rotary converter (as in the case of a synchronous motor) causes the converter to fall out of synchronism and stop, or "break down," as it is termed.

Compound-wound rotary converters are used to advantage for supplying current which is constantly fluctuating (and where the generators supplying the converters do not greatly exceed the latter in kilowatt capacity) as in railway service, and in cases where it is necessary to maintain constant or increasing voltage with increasing load. More or less prominence can be given to shunt or series windings as may be required.

The regulation is made automatic by a series field winding on the converter, but the inductance of the transmission lines and generator must frequently be increased by introducing reactive coils.

The amount of raising ("boosting") or lowering of the voltage is proportional to the reactance in circuit, for a given series field. Considering, however, that the maximum output of the converter and its stability are affected by too much reactance, the introduction of reactance should not be carried too far.

In compound-wound converters the shunt excitation is generally adjusted to give a lagging current of from 20% to 30% of full load current at no load by under-excitation, and the series field is adjusted to give a slightly leading current at full load. This arrangement lowers the impressed voltage at the converter at no load and raises it at full-load enough (with constant voltage at the generator) to compensate for all the losses of voltage in the system, thus making possible the delivery of a constant direct-current voltage at all loads.

It has been found in practice that the compound winding distinctly diminishes the stability of running when the tendency to hunt is present to any extent. The series winding should be cut out when starting up from the direct-current side. This is conveniently accomplished by a double-throw switch which in one position connects the junction of the series winding and the negative brushes to the starting rheostat, and in the other position connects this junction with the equalizing bar.

4. *Separate Excitation.* The use of a small auxiliary direct-current dynamo to supply direct current for exciting the field of a rotary converter has been mentioned in Art. 128, where it was

pointed out that this method of field excitation is especially suited to inverted rotaries.

131. The Rotary Converter with the Edison Three-wire System. The Edison three-wire system must ordinarily be supplied with current from two direct-current generators connected in series between the outside mains, and with the neutral main connected to the junction of the two machines.

To operate a three-wire system from a single direct-current generator would give rise to great differences of voltage on the two sides of the system when the number of lamps on one side differs greatly from the number of lamps on the other side; in fact it would not be allowable to turn off a lamp on one side without turning off a lamp on the other side at the same time. To avoid this difficulty some arrangement which is equivalent to the use of two generators is necessary.

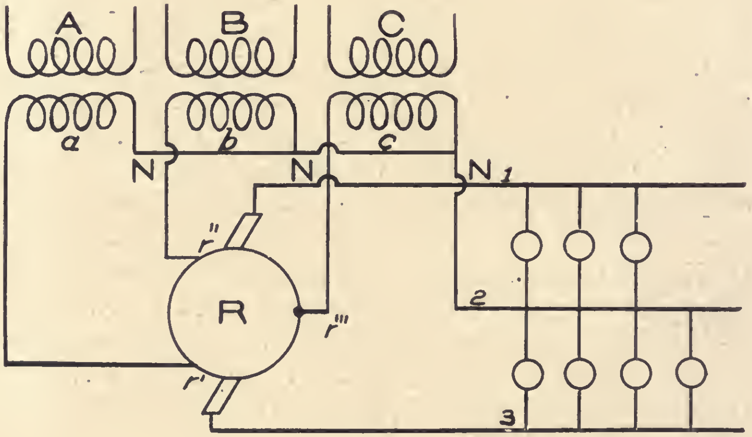


Fig. 275.

A rotary converter may be used to deliver direct current to an Edison three-wire system giving every advantage ordinarily obtained by the use of two direct-current generators connected in series. The connections of a three-phase rotary converter for supplying direct current to an Edison three-wire system, are shown in Fig. 275.

The three primaries A, B, and C of the step-down transformers for supplying alternating currents to the rotary converter, are,

5,000 K. W. ENGINE TYPE A. C. GENERATORS, THREE-PHASE, 11,000 VOLTS, 25 CYCLES
75 R. P. M.—74th STREET STATION INTERBOROUGH RAPID
TRANSIT COMPANY, NEW YORK

Westinghouse Electric & Manufacturing Co.

either Y- or Δ-connected to the high voltage supply mains. The three secondaries, *a*, *b*, and *c* are Y-connected to the collector rings, r', r'', r''', of the rotary converter. The two outside direct-current mains, 1 and 3, are connected to the direct-current brushes of the converter as shown, and the middle main (neutral main) 2, is connected to the common junction, N, or neutral point, of the Y-connected secondaries, *a*, *b*, and *c*. With these connections, the voltage between mains 1 and 2 is a steady direct-current voltage, as is also the voltage between mains 2 and 3, and each of these voltages is equal to half the voltage between mains 1 and 3. When the number of lamps connected between mains 1 and 2 is different from the number connected between mains 2 and 3, or *vice versa*, the neutral main must carry a direct current equal to the difference of the direct currents in the mains 1 and 3. This direct current in the neutral main 2 is actually supplied through the secondary coils *a*, *b*, and *c* from the collector rings.

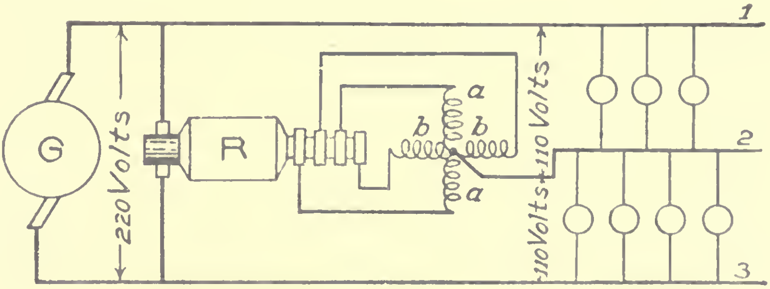


Fig. 276.

Fig. 276 shows an ordinary direct-current generator G, supplying current to the outside mains 1 and 3, of an Edison three-wire system, and a two-phase rotary converter R, connected as a "balancer" to supply the necessary direct current to the middle main 2. The armature only of the rotary converter is shown in the figure, its direct-current brushes being connected to the outside mains 1 and 3. One pair of opposite collector rings of the converter R is connected to an inductance coil *a a*, wound on an iron core, and the other pair is connected to an inductance coil, *b b*. The middle point of these two inductance coils are connected together, and to the middle or neutral main 2, of the three-wire system.

132. The Six-Phase Converter. The large rating of a six-phase converter, as shown in the table given in article 116, together with other advantages enumerated below, make this machine the standard converter, especially for large substations. The advantages of the six-phase converter are as follows:

(a) The high rating, namely, 1.92 times the rating of the same machine as a direct-current generator, or 1.45 times the rating of the same machine as a three-phase converter, means that the machine may be smaller and therefore cheaper for a given output. The high rating of the six-phase converter is due to the fact that its armature winding is tapped at six points (for a two-pole machine), and that alternating currents enter the armature winding at six points, so that the length and resistance of the paths from collector rings to commutator are less, and the heating of the armature windings is less than it is in a three-phase converter, for example, for the same direct-current output.

(b) The six-phase converter runs more stably than a converter having a smaller number of collector rings, and has less tendency to hunt.

(c) The magnetizing actions of the alternating and direct currents in the armature are more nearly balanced in the six-phase converter than in a converter having a fewer number of collector rings, and commutation is freer from sparking and flashing.

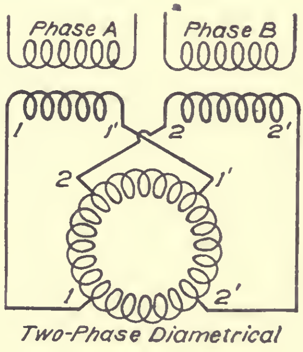


Fig. 277.

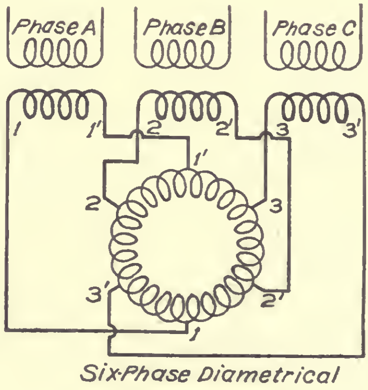
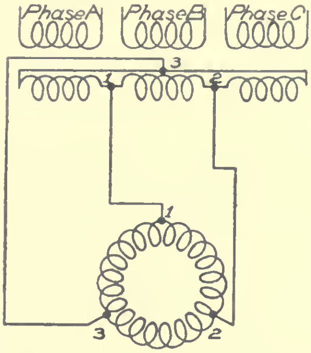


Fig. 278.

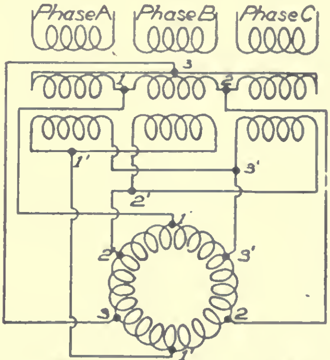
133. Transformer Connections for Rotary Converters. Figs. 277 to 284 show the connections which are commonly employed between transformers and rotary converters. The circular spiral winding at the bottom of each figure represents the armature winding of a bipolar converter, the collector rings being omitted to avoid confusing the diagram. Figs. 277, 279, 281, and 283 show the two-phase and three-phase connections, while figures 278, 280, 282, and 284 are for six-phase connection.

Each pair of figures, 277 and 278, 279 and 280, 281 and 282, 283 and 284 are closely related. Thus in Figs. 277 and 278, the two terminals of each transformer secondary coil are joined to the armature winding of the converter at points 180° apart. Such connection is called the diametrical connection. The diametrical connection is possible when the rotary has an *even* number of rings. In any diametrical connection of the secondaries of the step-down transformers (one transformer for a two-ring converter, two transformers for a four-ring converter, and three transformers for a six-ring converter), the voltage in each secondary coil is the same in value, no matter how many rings the converter may have.



Three-Phase Δ Connection

Fig. 279.



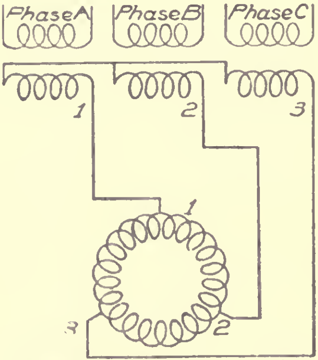
Six-Phase Double Δ Connection

Fig. 280.

The diametrical connection of the transformer secondaries to the converter rings is simpler than the connections shown in Figs. 280, 282, and 284, inasmuch as the diametrical connection requires only one secondary coil on each of the step-down transformers, and therefore but two secondary leads are brought out from each transformer; whereas the connections shown in Figs. 280, 282, and 284 require two secondaries on each transformer, and therefore four secondary leads from each transformer. The switching arrangements for the diametrical connection are therefore simpler than they are for the connections shown in Figs. 280, 282, and 284.

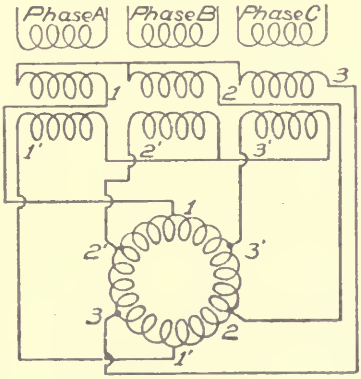
Fig. 279 shows three step-down transformers receiving three-phase currents, and delivering three-phase currents to a rotary converter, the secondaries being connected to the collector rings. Fig. 281 shows the same arrangement except that the secondaries are Y-connected to the collector rings. Fig. 283 shows a Scott* transformer receiving currents from two-phase supply mains and delivering three-phase currents to a three-ring converter. This Scott transformer arrangement is often called the T-connection, and it may be adapted with slight modification to three-phase supply, that is, to transform three-phase alternating currents into two-phase alternating currents.

For three-phase rotary converters, the transformers should preferably be connected in Δ, as this permits the system to be operated with only two transformers, in case the third has to be cut out of the circuit temporarily for repairs.



Three-Phase Y Connection

Fig. 281.



Six-Phase Double Y Connection

Fig. 282.

The T-connection as shown in Figs. 283 and 284 requires only two transformers, and it can be used to change from either two-phase or three-phase to three-phase as shown in Fig. 283, or from two-phase or three-phase to six-phase as shown in Fig. 284. The Y- or T-arrangement of transformers is particularly advantageous where a rotary is to be used to supply direct current to an Edison three-wire system. Of course, two converters can be used, one on each branch of the three-wire system, and this is the preferable method where the branches are liable to be greatly unbalanced.

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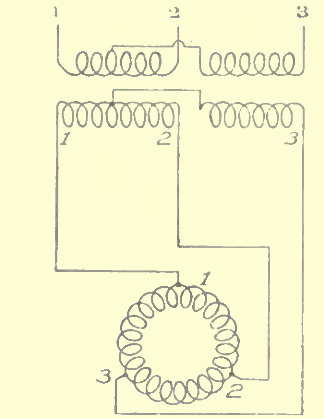
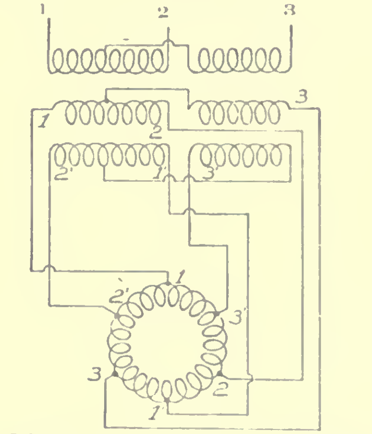
*The principle of phase transformation is explained in detail in article 101

With the Y- or T-connection of transformers a single converter can be connected across the outside wires of the three-wire system, the neutral wire can then be joined to the neutral point of the Y-connection, or to a tap, in one of the transformer windings, which tap corresponds to the neutral point of the Y-connection.*



Three-Phase T-Connection

Fig. 283.



Six-Phase Double T-Connection

Fig. 284.

TESTING OF ROTARY CONVERTERS.

Saturation Curve. Core Loss. Phase Characteristic. Pulsation.

134. For a rotary converter, the saturation and core loss curves are obtained in the same manner as in the case of an alternating-current generator, with the exception that the direct-current voltage is also recorded. The phase characteristic is determined and the pulsation test is made in the same manner as for a synchronous motor, except that the direct-current voltage should be recorded. The machine, of course, is run as a synchronous motor, being supplied with alternating current through its collecting rings. The pulsation test should be made with the converter self-excited.

135. Heat Run. To make a heat run on a rotary converter it may be run either as a synchronous motor taking alternating currents through its collector rings, or as a direct-current motor supplied with direct current through its brushes and commutator. If driven as a synchronous alternating-current motor, the full load output is taken from the commutator end of its armature (or *vice* *versa*) and is delivered to a water rheostat or other receiver. During the run the following readings should be recorded every half hour:

Volts D.C.	Volts A.C.	Amperes D.C.	Amperes A.C.	Amperes Field.	Volts Field.	Speed.	Room Temp.

When the rotary converter has reached a constant temperature, after running continuously a number of hours under rated full load conditions, the machine may be shut down, and thermometers quickly applied to measure the temperature of the following parts:

Armature laminations.
Armature ventilating ducts.
Armature coils front end.
Armature coils back end.
Armature binding wires.
Commutator.
Collector rings.
Field spools.
Pole tip, leading.
Pole tip, trailing.
Frame.
Bearings.
Room.

The condition of constant temperature is indicated when the voltage applied to the terminals of the field winding, in order to keep the current in the field winding constant, no longer increases. In other words, the resistance of the field winding increases for a time due to increasing temperature of the winding, and it takes an increasing voltage at the field terminals to maintain the field current constant. But when the temperature of the field windings becomes constant, the voltage required at the field terminals no longer increases.

If two similar rotary converters are at hand, the heat test may be made by the "motor-generator" method, in a manner somewhat similar to the method described under transformers (see article 109). This method applied to rotary converters involves running one machine as an inverted rotary taking power through its brushes and commutator from direct-current mains. The second machine is made to run as a regular rotary converter, taking its power from the collector rings (that is alternating-current side) of machine No. 1. Machine No. 2 then delivers its power in the form of direct current from its commutator back to the direct-current supply mains, or to the commutator of machine No. 1. Machines numbers 1 and 2 are now said to be "tied together in multiple on both the direct-current and the alternating-current sides". If the machines are similar in every respect, no appreciable current will flow between the two under these circumstances. Each will run from the direct-current side, the two together taking only enough power from the direct-current mains to supply the no-load losses in both machines. If, however, an auxiliary electromotive force is applied in the circuit between the machines on the alternating-current side, it will immediately cause current to flow between the machines precisely as in the case of the transformer test above referred to.

Fig. 285 is a diagram of the electrical connections for this method of running. R_1 and R_2 are the two three-phase rotaries.

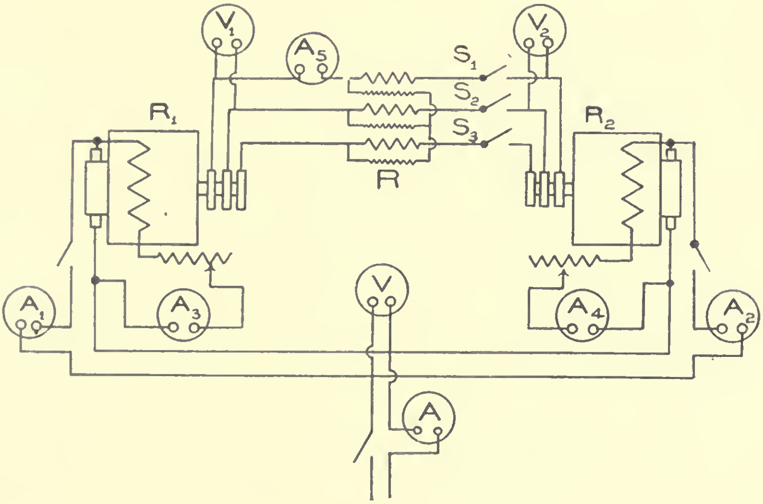


Fig. 285.

They are shown connected together electrically on the alternating-current side (that is, the collector rings of R_1 are connected to the corresponding collector rings of R_2) through the induction regulator* R. This regulator supplies to the circuit of each phase the auxiliary electromotive force necessary to cause the current to flow between the two machines. The electromotive forces supplied by the regulator are adjustable. When the machines are first thrown together the regulator is in such a position that its electromotive forces are zero.

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* Described later.

On the direct-current side (commutator ends) both machines are shown electrically connected to the dirrect-current supply mains.

The method of procedure in starting the two machines is as follows:

First R_1 is started as a direct-current motor from the direct-current side (commutator). Its field current is adjusted until it runs at the right speed when the normal voltage is applied to its armature terminals; R_1 is at this time entirely disconnected from R_2. Next R_2 is started in the same manner. Then R_1 and R_2 are synchronized and connected together, as shown in the diagram, by closing switches S_1, S_2, and S_3 on the alternating-current side.

The apparatus for determining when the two machines are in synchronism is not shown in the figure. The most convenient way to synchronize the machines for testing is to connect up a series of incandescent lamps across each of the switches S_1, S_2, and S_3. The number of incandescent lamps in each series should be such that they can stand twice the normal alternating voltage of each machine.

The field current of R_2 is varied until it is almost in synchronism with R_1, as shown by the slow pulsations of the synchronizing lamps. When the lamps are dark, there is zero voltage across the terminals of the switches, and then they can be safely closed. If the lamps connected across the switches do not all go out at the same instant, the machines cannot be synchronized. In this case the direction of rotation of one of the machines must be reversed, or two of the leads on the alternating-current side of one of the machines must be interchanged.

Up to this time the two machines have been running independently of each other. Each has taken sufficient current from the mains to supply the losses occurring in it while running unloaded. When the two machines are connected together on the alternating-current side by closing the switches S_1, S_2, and S_3, they run in synchronism. If the regulator R is in its zero position, no appreciable current will flow between the two machines. As the voltage of R is increased, however, a current will circulate between the two machines. If the voltage of R is in such a direction that V_2 is greater than V_1, then R_2 will run as a regular rotary converter, and R_1 as an inverted rotary. The power will pass from R_1 to R_2 on the alternating-current side, and from R_2 to R_1 on the direct-current side. R_1 will run as an inverted rotary, driving R_2 on the alternating current side, and R_2 will run as an ordinary rotary converter driving R_1 on the direct-current side.

By sufficiently increasing the voltage of R we can cause full-load or even over-load conditions to obtain. The direct-current mains deliver merely the power to supply the losses in the entire system. Ammeter A indicates the current supplied to overcome the losses in the system. Under these circumstances, R_1 will have a load slightly greater than R_2. Ammeter A_1 should give a reading equal to the sum of the readings of the two ammeters A and A_2.

The chief advantage of this method is that full-load conditions are obtained without actually supplying full-load current from the direct-current supply mains. The mains supply simply the power losses in both machines. Another great advantage is the ease with which the load can be controlled. By this method, moreover, two machines can be tested more easily than a single machine by the ordinary method. If it is desired to test one machine only, the load may be put on in the same way by connecting it up with a second machine. It is not necessary in this case that the second machine be of the same size as the first. It is only necessary that it be of the same voltage and frequency, and that it can carry without excessive heating the full-load current of the machine to be tested. The current, during the run, is adjusted to the normal full-load value of the machine to be tested.

THE INDUCTION MOTOR.

136. It has already been pointed out that the successful use of alternating current for power purposes depends largely upon the use of the *induction motor* supplied with polyphase currents. This machine consists of a primary member and a secondary member, each with a winding of bars or wire. The primary member is usually stationary, and is often called the *stator*. The secondary member is usually the rotating member, and is often called the *rotor*. Fig. 286 shows a rotor of the *squirrel-cage* type. It consists of a drum A built up of circular sheet-iron discs. Near the periphery of this drum are a number of holes parallel to the axis of the drum. In these holes heavy copper rods *b* are placed, and the projecting ends of these rods are screwed and soldered to massive copper rings *r*, one at each end of the drum. Other types of rotor are described later.

The stator is a laminated iron ring, FF, Fig. 287, closely surrounding the rotor. This ring is slotted on its inner face, as shown; windings are arranged in these slots, and these windings receive current from polyphase supply mains. These polyphase currents produce in the stator iron a rotating state of magnetism, the action of which on the rotor is the same as the action of an ordinary field magnet mechanically revolved. Thus Fig. 288 shows a squirrel-cage rotor A, surrounded by an ordinary field magnet revolving in the direction of the arrows. This motion of the field magnet induces currents in the short-circuited copper rods of the rotor; the field magnet exerts a dragging force on these currents, and causes the rotor to revolve.

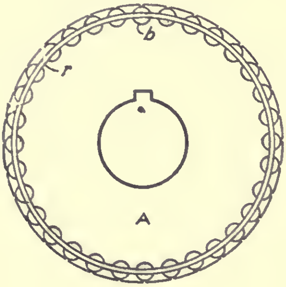

Fig. 286.

No electrical connections of any kind are made to the rotor.

137. Stator Windings and Their Action. The stator windings are arranged in the slots *s*, Fig. 287, in *a manner exactly similar to the arrangement of the windings of the two-phase or three-phase alternator armature*, according as the motor is to be supplied with two-phase or three-phase currents.

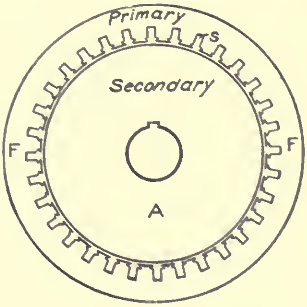

Fig. 287.

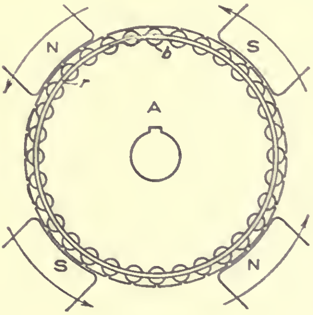

Fig. 288.

Fig. 289 shows an end view of a four-pole two-phase induction motor. In this figure, the outline only of the rotor (or secondary) is shown. The stator conductors are represented in section by the small circles, the slots being omitted for the sake of clearness, and the end connections of half the stator conductors are shown in Fig. 290. In this figure the straight radial lines represent the conductors which lie in the slots of the stator, and the curved lines represent the end connections. The stator conductors are arranged in two distinct circuits. One of these circuits includes all of the conductors marked A, and this circuit receives current from one phase of a two-phase system. The other circuit includes all of the conductors marked B and this circuit receives current from the other phase of the two-phase system. The terminals of the B circuit are shown at t t', Fig. 290. The conductors which constitute one circuit are so connected that the current flows in *opposite directions* in adjacent groups of conductors as indicated by the arrows in Fig. 290.

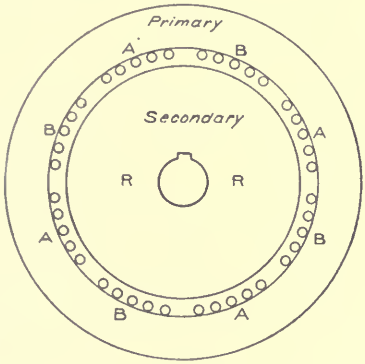

Fig. 289.

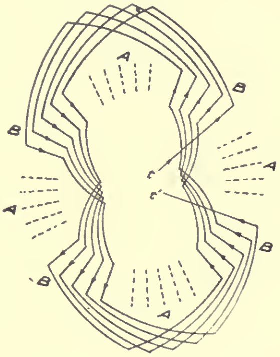

Fig. 290.

The action of a band of conductors between the two masses of iron is shown in Figs. 291 and 292. The small circles represent the conductors in section; conductors carrying down-flowing currents are marked with crosses and those carrying up-flowing currents with dots. The action of the currents in these bands of conductors is to produce magnetic flux along the dotted lines in the direction of the arrows.

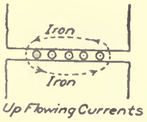

Fig. 291.

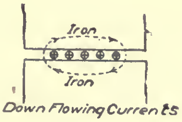

Fig. 292.

The lines A′ and B′ in the clock diagrams of Figs. 293, 294, and 295 are supposed to rotate, and their projections on the fixed line *ef* represent the instantaneous values of the alternating currents in the A and B conductors respectively. These conductors are represented in section by the small circles. These small circles are marked with crosses when they carry down-flowing currents, with dots when they carry up-flowing currents, and they are left blank when they carry no current.

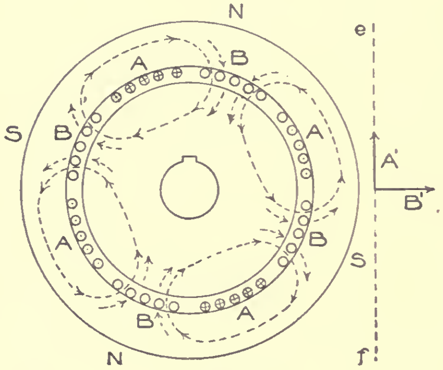

Fig. 293.

Fig. 293 shows the state of affairs when the current in conductors A is a maximum and the current in conductors B is zero, and the dotted lines indicate the paths of the magnetic flux. This flux enters the rotor from the stator at the points marked N and leaves the rotor at the points marked S.

Fig. 294 shows the state of affairs, one-eighth of a cycle later, when the current in the B conductors has increased and the current in the A conductors has decreased to the same value, so that equal currents flow in the A and in the B conductors. The points N and S have moved over one-sixteenth of the circumference of the stator ring, from the positions they occupied in Fig. 293.

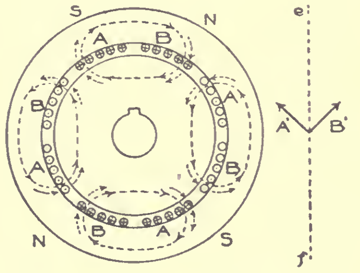

Fig. 294.

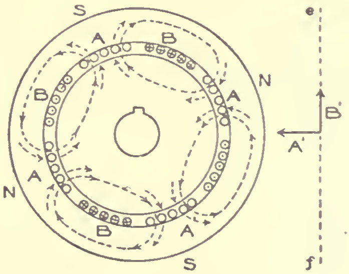

Fig. 295.

Fig. 295 shows the state of affairs, after another eighth of a cycle, when the current in the B conductors has reached its maximum value, and the current in the A conductors has dropped to zero. The points N and S have moved again over one-sixteenth of the circumference of the stator ring. This motion of the points N and S is continuous, and these points make one complete revolution (in a four-pole motor) during two complete revolutions of the vectors A′ and B′, that is, while the alternating currents supplied to the stator windings are passing through two cycles. In general:

$$n = \frac{2f}{p}$$

in which n is the revolutions per second of the stator-magnetism, p is the number of poles (N and S), and f is the frequency of the alternating currents supplied to the stator windings.

Three-Phase Stator Winding. When an induction motor is driven by three-phase currents, the stator conductors are arranged in three distinct circuits A, B, and C, which are either Δ-connected or Y-connected to the supply mains. Fig. 296 shows the complete connections, for four poles, of the A circuit with its terminals $t\ t'$. The B and C circuits are similarly connected.

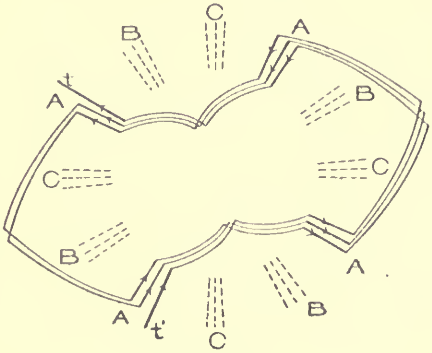

Fig. 296.

In general, the q-phase stator winding for p poles has $p\,q$ equidistant bands of conductors. The 1st, $(q + 1)$th, $(2q + 1)$th, etc., bands are connected in one circuit, so that currents flow oppositely in adjacent bands, and this circuit takes current from one phase of the q-phase system. The 2nd, $(q + 2)$th, $(2q + 2)$th, etc., bands are similarly connected in another circuit and take current from the second phase of the q-phase system. The 3d, $(q + 3)$th, $(2q + 3)$th, etc., bands are similarly connected in another circuit and take current from the third phase of the q-phase system; and so on.

138. Discussion of the Action of the Induction Motor. Many important details of the action of the induction motor are most easily explained by looking upon the induction motor as a rotor influenced by an ordinary field magnet, mechanically revolved. The complete theory of the action of the induction motor is, however, similar to the theory of the alternating current transformer.

Torque and Speed. Let n be the number of revolutions per second of the field, and n' the revolutions per second of the rotor. When $n = n'$, the rotor and field revolve at the same speed, so that their *relative* motion is zero; no electromotive force is then induced in the rotor conductors and no current flows, and therefore the revolving field exerts no torque upon the rotor. As the speed of the rotor decreases, the difference of the speeds of rotor and field $(n - n')$, increases, and therefore the electromotive force induced in the rotor conductors, the currents in the conductors, and the torque with which the field drags the rotor, all increase. If the whole of the field flux were to pass into the rotor and out again in spite of the demagnetizing action of the current in the rotor conductors, then the torque would increase in strict proportion to $(n - n')$. As a matter of fact, because of the demagnetizing action of the rotor currents, a larger and larger portion of the field flux passes through the space between the stator and rotor conductors as the speed of the rotor decreases, and this magnetic leakage causes the torque to increase more and more slowly as $(n - n')$ increases. The torque usually reaches a maximum value, and then decreases with further increase of $(n - n')$.

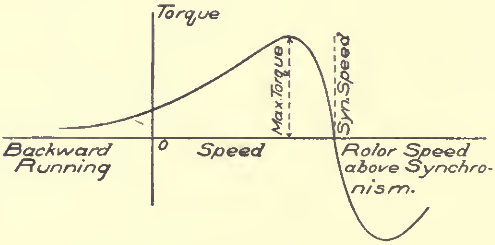

Fig. 297.

Fig. 297 shows the typical relation between torque and speed of an induction motor. Ordinates of the curve represent torque, and abscissas measured from 0 represent rotor speeds. The rotor is said to run above synchronism when it is driven so that n' is greater than n. The rotor never actually reaches synchronous speed, but approaches it very nearly when the induction motor is running unloaded. In order to cause the rotor to run above synchronism, that is, to make n' greater than n, or in order to cause the rotor to run backwards (that is, in a direction opposite to that of the revolving magnetism in the stator iron), the rotor must be driven mechanically from an outside source of power.

Starting Resistance in the Rotor Windings. The speed of the rotor for which the maximum torque occurs, depends upon the resistance of the rotor windings, and it is advantageous under certain conditions of operation to provide at starting such resistance in these windings as to at once produce the maximum torque, this resistance being cut out as the motor approaches full speed. A detailed description and discussion of rotors furnished with starting resistances is given in article 139.

Efficiency and Speed. For the sake of simplicity, let us assume that the only opposition to motion of the revolving field magnet is the reaction of the torque which it exerts on the rotor. Let this torque be represented by T. Then the power expended in driving the field magnet is $2\pi n\mathrm{T}$, and the mechanical power delivered to the rotor is $2\pi n'\mathrm{T}$, and this power $2\pi n'\mathrm{T}$ is available at the pulley of the motor, except for slight losses due to friction in the bearings, and air friction. Therefore, ignoring friction losses, $2\pi n\mathrm{T}$ is the input of power in driving the revolving field, and $2\pi n'\mathrm{T}$ is the output of power, so that

$$\text{The efficiency of the induction motor} = \frac{n'}{n}.$$

This expression for efficiency ignores all the losses of power in the revolving field magnet (in the actual induction motor, it ignores the loss of power due to the heating of the stator windings by the supplied alternating currents, and the loss of power due to core losses in the stator iron), and the friction and windage losses in the rotor. This equation shows that the efficiency of an induction motor is zero when the rotor stands still, that it increases as the rotor speeds up, and approaches 100% (*ignoring field losses and friction*), as the rotor speed approaches the speed of the revolving field. The ratio $\frac{n'}{n}$ ranges from 0.85 to 0.95 or more, in commercial induction motors under full load, but the actual full load efficiencies of induction motors range from 75 per cent, or even less for small motors, to about 93 per cent for large motors.

Ratio of Mechanical to Electrical Energy in the Rotor. The total power delivered to the rotor is equal to $2\pi n\mathrm{T}$ where n and T have the meanings above specified. That is, all of the power used to drive the field magnet (ignoring losses in the field) is delivered to the rotor. Now, the mechanical power delivered to the rotor is equal to $2\pi n'\mathrm{T}$, as already explained; therefore, the difference $2\pi n\mathrm{T} - 2\pi n'\mathrm{T}$* is electrical power used to force the rotor currents through the rotor windings.

Therefore, when the field speed is n and the rotor speed is n', the total power delivered to the rotor, the mechanical power developed in turning the rotor, and the electrical power developed in the rotor windings are to each other as, n, n' and $(n - n')$ respectively.

Ratio of Rotor Voltages to Stator Voltages. When the rotor is wound with the same number of conductors as the stator, then when the rotor is standing still, the rotating stator magnetism induces in the rotor windings electromotive forces of the same value and of the same frequency as the electromotive forces induced in the stator windings by this rotating stator magnetism (neglecting magnetic leakage). Moreover, the electromotive forces induced in the stator windings are very nearly equal and opposite to the voltages applied to the stator windings. When the difference of the speeds of the rotor and the stator magnetism is $(n - n')$, the electromotive forces induced in the rotor windings are the fractional part, $\left[\frac{n - n'}{n}\right]$, of the voltages applied to the stator windings, and the frequency of the electromotive forces induced in the rotor windings is the fractional part, $\left[\frac{n - n'}{n}\right]$, of the frequency of the voltages applied to the stator windings.

Examples. Let a certain three-phase induction motor having a stator wound for 6 poles, and taking three-phase alternating cur-

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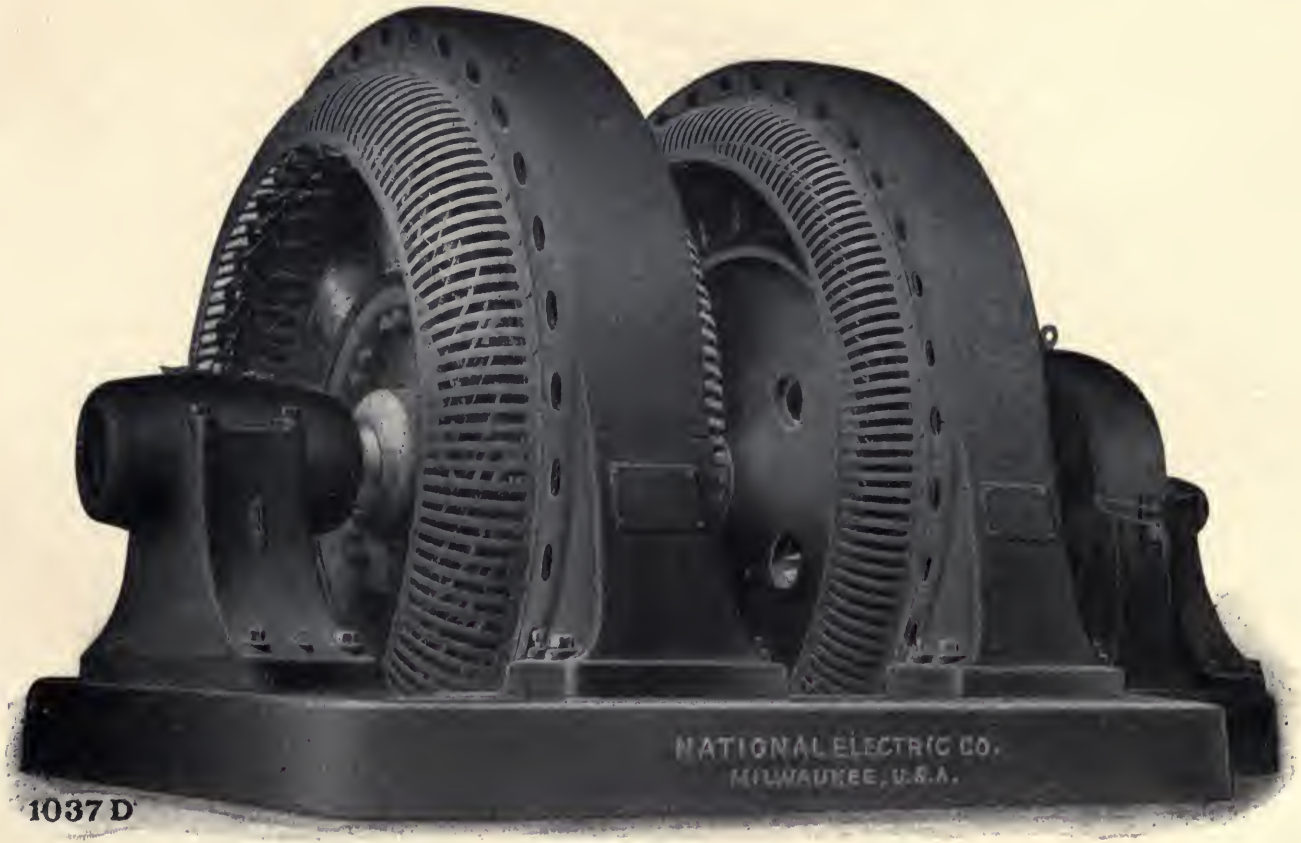
* When torque is expressed as pounds weight on a lever arm of one foot in length the torque is said to be expressed in pound-feet, and power in watts is equal to $\frac{2\pi n\mathrm{T} \times 746}{550} = 8.52n\mathrm{T}$ watts, where n is the speed in revolutions per second.



1,000 K. W. FREQUENCY CHANGING SET

National Brake & Electric Co

rents at a frequency of 60 cycles and a voltage of 220 between any two of the three supply mains, have a rotor furnished with the same number of conductors as the stator. Further, let the no-load speed of the rotor be 1194 r.p.m., and its full-load speed be 1143 r.p.m. Assume that the magnetic leakage is negligible.

It is required to find;

(*a*) The synchronous speed.

(*b*) The electromotive forces (three-phase) induced in the rotor windings at no-load and at full-load.

(*c*) The frequency of the electromotive forces induced in the rotor windings at no-load and at full-load.

Solution: (*a*) The synchronous speed of the rotating magnetism in the stator is, according to equation on page 313

$$n = \frac{60}{\frac{6}{2}} = 20 \text{ revolutions per second or } 1{,}200 \text{ r.p.m.}$$

(*b*) The electromotive forces (three-phase) induced in the rotor windings at no-load are

$$\frac{(n - n')}{n} \times \text{voltage applied to stator}$$

or

$$\left(\frac{1200 - 1194}{1200}\right) \times 220 = 1.10 \text{ volts.}$$

The voltages induced in the rotor windings at full-load are:

$$\left(\frac{1200 - 1143}{1200}\right) \times 220 = 10.45 \text{ volts.}$$

It is interesting to note that if the slip of the rotor at no load were zero, or in other words, if n' were equal to n, there would be zero electromotive forces induced in the rotor windings at no-load.

(*c*) The frequency of the electromotive forces induced in the rotor windings at no-load is

$$\frac{(n - n')}{n} \times \text{frequency of stator voltage}$$

or

$$\left(\frac{1200 - 1194}{1200}\right) \times 60 = 0.3 \text{ cycles per second.}$$

Fig. 298.

Fig. 299.

Fig. 300.

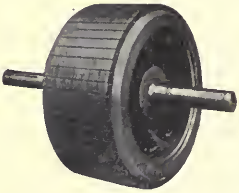


Fig. 301.

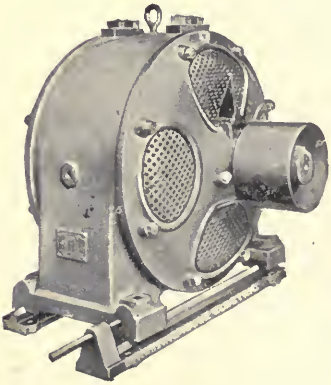


Fig. 303.

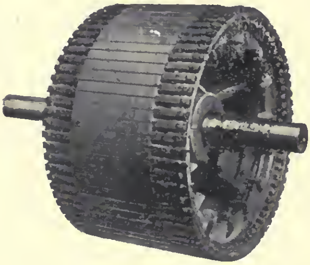


Fig. 302.

The frequency of the electromotive forces induced in the rotor windings at full-load is:

$$\left(\frac{1200 - 1143}{1200}\right) \times 60 = 2.85 \text{ cycles per second.}$$

When the rotor is at rest, the frequency of the electromotive forces induced in the rotor windings is the same as the frequency of the stator voltage, namely, 60 cycles per second.

Efficiency and Rotor Resistance. For a given difference $(n - n')$ between field speed and rotor speed, a definite electromotive force is induced in the rotor conductors, and the less the rotor resistance, the greater the current produced by this electromotive force, and the greater the torque. Therefore a given induction motor will develop its full load torque for a small value $(n - n')$ or for a large value of $\frac{n'}{n}$ (efficiency) if its rotor resistance is small. High efficiency depends, therefore, upon low rotor resistance.

The necessity of high rotor resistance to give large torque at starting has nothing to do with the necessity of making the rotor resistance small in order to secure full load torque at as nearly synchronous speed as posible. These two conflicting conditions may be realized in one motor by an arrangement whereby a resistance which is in circuit with the rotor conductors at starting, may be short-circuited when the motor nearly reaches its rated speed.

139. *Structural Details of a Typical Induction Motor.* Figs. 298 to 303 show the structural details of a typical induction motor manufactured by the Westinghouse Electric and Manufacturing Co. It has a stationary primary member (often called the stator or field) and a rotating secondary member (often called the rotor or armature). The primary member is mounted in a hollow cylindrical frame of cast-iron shown in Fig. 298. This frame forms a base for the machine, and also supports the two end-plates which carry the self-oiling bearings. The iron core of the primary member consists of a ring built up of sheet-steel stampings slotted on the inside to receive the primary conductors as shown in Fig. 299. The stampings are rigidly supported by the cast-iron housing. In motors of large size, each stamping is not a complete ring, but a segment, and these segments are dovetailed into grooves on the inner face of a hollow cylindrical shell of cast-iron which is held in the cast-iron frame of the motor. Fig. 300 shows the primary member completely wound.

The primary conductors are usually grouped in machine-wound coils of wire which are thoroughly taped and insulated before being slipped into place in the slots in the primary iron core. In larger motors a copper strap bent into the proper form is used instead of wire for forming the coils.

The terminals of the primary winding are brought out to terminal blocks of porcelain which are mounted sometimes at the top, and sometimes at the side of the frame, and the leads which supply alternating currents to the motor are attached to these terminal blocks.

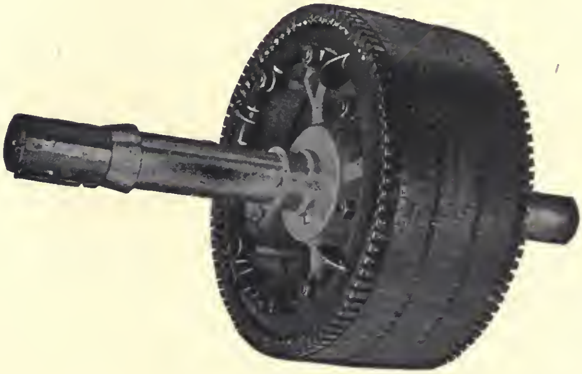


Fig. 304.

The iron core of the secondary member shown in Fig. 301, is built up of ring-shaped stampings of sheet-steel mounted upon a spider. The secondary conductors consist of rectangular copper bars placed in nearly closed slots around the periphery of the core. These bars project beyond the laminated core, and they are screwed and soldered at each end, to massive rings of copper, thus forming a short-circuited secondary winding as shown in Fig. 302. This type of secondary member is called the *squirrel-cage* rotor.

The complete motor is shown in Fig. 303. The large openings in the end-plates are covered with perforated iron plates, or gratings, which not only permit of thorough cooling of the machine by ventilation, but also serve to protect the motor from injury. No electrical connections whatever are made to the secondary member.

Three Types of Secondary Members. There are three types of secondary members used in commercial induction motors. These types are shown in Figs. 304, 305, and 306.

Fig. 304 is a squirrel-cage rotor. Fig. 305 is a rotor wound with insulated wire, forming what is called a *definite* * or *polar* winding. The terminals of this winding are connected to a starting resistance mounted inside of the rotor. A switch is arranged to short-circuit this starting resistance, and this switch is operated while the motor is running by means of a rod which lies inside of the hollow shaft of the rotor. This rod terminates in a small button or knob at the end of the rotor shaft as shown in Fig. 305. Fig. 312 shows a complete three-phase induction motor with the knob and rod for operating the internal starting resistance.

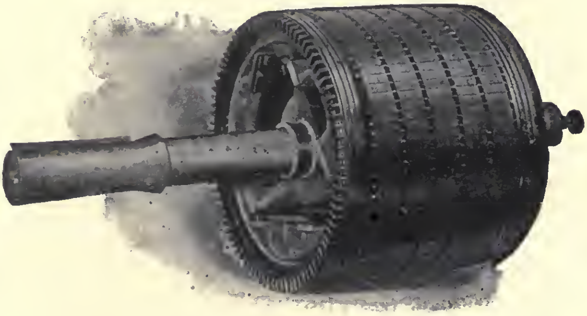


Fig. 305.

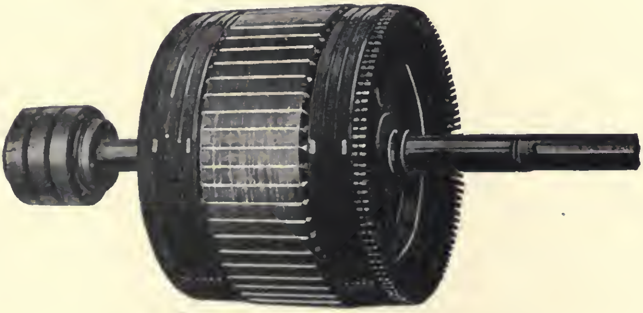


Fig. 306.

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*This winding is identical with the stator winding as described in article 137.

Fig. 306 is a rotor with a winding similar to the winding of Fig. 305, but instead of connecting the terminals of the rotor winding to an internal starting resistance, these terminals are brought out to collector rings on the end of the shaft as shown in Fig. 306. The circuits of the rotor windings are completed through adjustable external resistances which are connected to the rotor windings by means of brushes rubbing on the collector rings. These adjustable external resistances are regulated by a cylindrical switch or controller similar to the ordinary electric street car controller.

The cylinder has a set of contacts for making, breaking, and reversing the primary circuit, and another set of contacts for controlling the secondary resistance. At the first step, one phase of the Y-connected secondary circuit is open, making it possible to obtain a low current at starting with a much smaller amount of resistance.

A resistance is inserted in the primary leads for the purpose of distributing the arcing at the contact fingers, but it is not used for the purpose of speed control.

An induction motor provided with a squirrel-cage rotor takes excessive current from the alternating-current supply mains at starting. The squirrel-cage rotor requires from three to four times full-load current to produce at starting a torque equal to the torque developed when running at full-load. Hence, when the motor has to start under a heavy load, or where the taking of excessive currents from the supply mains will interfere with other apparatus supplied from the same mains by causing excessive drop of voltage, the squirrel-cage type of rotor is objectionable, especially in large size motors. On the other hand, the extreme simplicity of the squirrel-cage rotor and its ability to carry enormous currents without injury, largely compensate for the above mentioned disadvantages.

An induction motor provided with a rotor like that shown in Fig. 305, with an internal starting resistance, takes at starting only about full-load rated current from the supply mains, giving a starting torque about equal to full-load torque. Such an induction motor, therefore, is used only where a starting torque not greatly in excess of full-load torque is required. The advantage of this type of rotor is that it does not take excessive currents at starting, and it will start, therefore, without producing excessive drop of electromotive force in the alternating-current system from which the motor receives its power. The starting resistance may be made of copper strips, or, as is usually the case, of iron, cast into a compact grid form, and having a number of contact points. The whole of this resistance is in series with the secondary winding at starting. As the motor increases in speed, a circular short-circuiting ring, encircling the shaft, is pushed in by the controlling rod, thus cutting out the resistance in as many successive steps as there are contact points.

An induction motor having a rotor provided with collector rings is generally used for cranes, hoists, elevators, and other work where variable speed is required. The starting resistance used in the type of rotor shown in Fig. 305, is designed to carry the rotor current for a short time only, that is, during starting; if kept continuously in circuit for the purpose of speed control, this starting resistance would become excessively hot. For speed control, therefore, an external resistance must be used.

The range of speed control possible in the case of an induction motor provided with a rotor having collector rings connected to external adjustable resistances, is about the same as the range of speed control obtainable with a shunt-wound direct-current motor having a regulating rheostat in its armature circuit.

140. Behavior of an Induction Motor at Starting and in Operation. When an induction motor is running without load, its speed is nearly equal to the speed of the rotating magnetic field, namely, synchronous speed. Under these conditions the stator takes only sufficient current to force the magnetic flux through the reluctance of the magnetic circuit, and to supply the I^2R losses of the stator windings, the core loss, and the friction and windage loss of the rotor.

When the motor is loaded, its speed decreases in nearly direct proportion to the load, from nearly synchronous speed at no-load to about 98 per cent of synchronous speed in the case of large motors, and to about 92 per cent of synchronous speed in small motors at full-load. Therefore, the induction motor is practically a constant-speed motor. The decrease in speed expressed as a percentage of synchronous speed is called the *slip* of the motor. The slip of large motors is thus about 2 per cent at full-load, and that of small motors is about 8 per cent at full-load.

When an induction motor is overloaded, it takes excessive current from the supply mains, and its torque increases up to a certain value of the slip (a definite value for a given motor). When loaded up to this point the machine is unstable, and the least additional loading causes the machine to "break down" or stop.

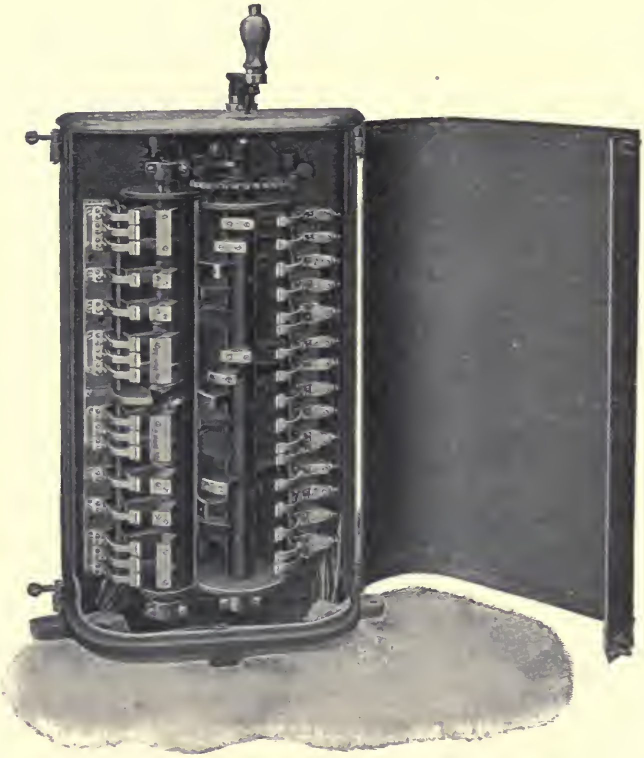


Fig. 307.

This maximum output which a given motor can deliver is usually about one and one-half to two times as great as its rated full-load output. This maximum output is proportional to the square of the electromotive force of the alternating currents supplied to the motor. Thus a certain induction motor rated at 220 volts has a *maximum* power output of 1.8 times its *rated* output. This same motor supplied with currents at 200 volts would have a maximum output of $\left(\frac{200}{220}\right)^2 \times 1.8 = 1.49$ of its rated output.

When an induction motor is operated at slightly less than its rated frequency but with full-rated voltage, the speed of the motor will be decreased in proportion to the frequency, but its power output will not be greatly affected. The efficiency of the motor, and its rise of temperature under full-load, will be approximately unchanged, and the maximum power output will be slightly increased.

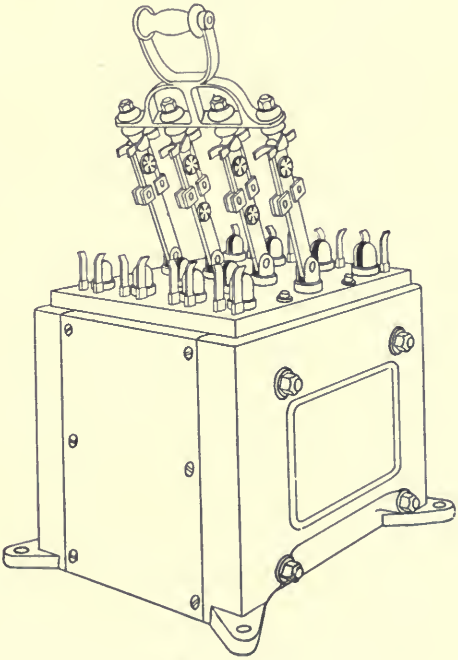
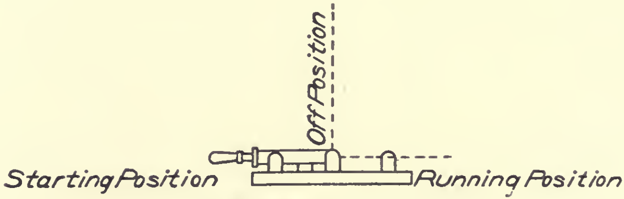


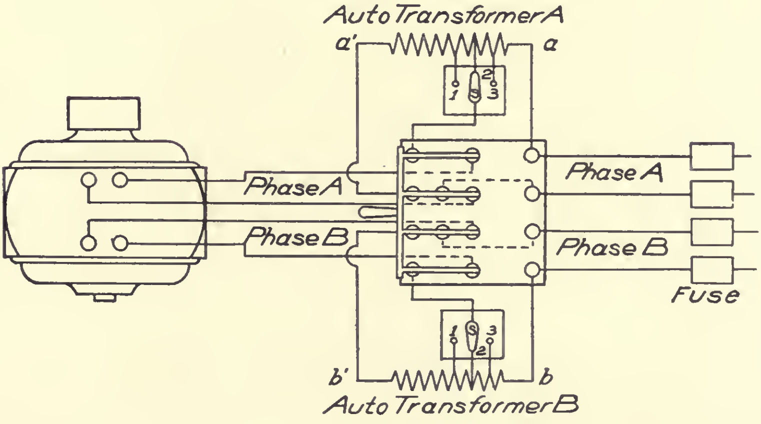
Fig. 308.

An induction motor having a squirrel-cage rotor will develop sufficient torque to start satisfactorily with from 40 per cent to 60 per cent of the rated voltage applied to the primary member. Therefore, the current required at starting may be greatly reduced by supplying the primary member, at starting, with current through a step-down transformer which is designed to reduce the supply voltage to 40, 50, or 60 per cent of the rated voltage of the motor, and to multiply the delivered current in the same ratio. This step-down transformer is usually an auto-transformer. This auto-transformer, with its special switching device for changing the motor connections quickly from the low-starting voltage to the full-running voltage, is called an *auto-starter*, or a *compensator*. The auto-starter may be located at any convenient point, either near the motor or at a distance from it.

Fig. 307 shows a General Electric controller for induction motors of 50 to 150 H.P. inclusive. Fig. 308 is a general view of an auto-starter or compensator as manufactured by the Westinghouse Electric and Manufacturing Co. Fig. 309 shows the complete connections of this starter to two-phase supply mains and to the terminals of a two-phase induction motor. A four-pole double throw switch, of which a side view is shown in the upper part of Fig. 309, disconnects everything from the supply mains when the switch lever is in the "off position". When the switch lever is in the "starting position", it connects the supply mains to the terminals a a' and b b' of the two auto-transformers, and at the same time it connects phase A of the motor to a section ($a'1$, $a'2$, or $a'3$) of the auto-transformer A, and also connects phase B of the motor to a section ($b'1$, $b'2$, or $b'3$) of the auto-transformer B, as may be seen by tracing the connections in Fig. 309. When the switch is



Side View of Switch



Top View of Switch

Fig. 309.

in the "running position," it connects the motor terminals directly to the supply mains, and disconnects the terminals a' and b' of the auto-transformers. To start the motor, the switch is thrown to the "starting position", and is left there until the motor reaches nearly full speed and then the switch is quickly thrown over to the "running position." The voltage for starting may be given a large, medium, or small value (say, 60 per cent, 50 per cent, or 40 per cent of the rated voltage) by throwing the two switches *s s* to tap points 1, 2, or 3, respectively. The time required for bringing an induction motor from rest up to rated speed varies from 10 seconds to 30 seconds, according to the value of the starting voltage used, and according to the amount of load on the motor at starting.

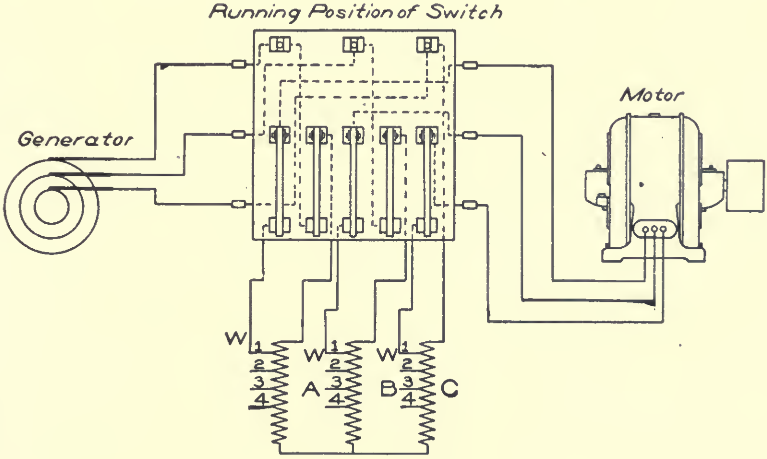


Fig. 310.

The direction of rotation of a two-phase motor is reversed by reversing the connections of one of the phases, that is, by reversing the connections of the two wires belonging to one-phase supplying current to the stator windings of the motor.

The direction of rotation of a three-phase (three-wire) motor is reversed by interchanging the connections of any two of the three wires used to lead the three-phase currents to the stator windings of the motor.

Fig. 310 shows the general arrangement and complete connections of a three-phase induction motor, with auto-starter, or compensator, manufactured by the General Electric Co. The compensator consists of three auto-transformers A, B, and C, each having a number of taps, 1, 2, 3, and 4, to any one of which the wires W W W may be connected; and a special five-pole, double-throw switch. The blades of this switch touch only three contact points when the switch-lever is in the "running position," and touch five contact points when the switch-lever is in the "starting position." This three-phase starting compensator is essentially similar to the two-phase starter, and the connections may be easily traced in Fig. 310.

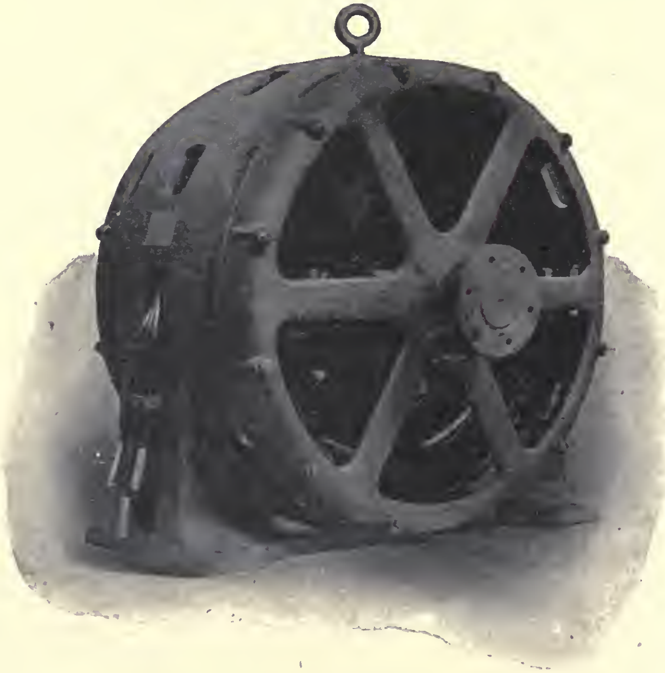


Fig. 311.

141. Typical Induction Motor Installations. Fig. 311 is a general view of a 500 horse-power Westinghouse induction motor, designed for direct coupling to its load. Such direct-coupled induction motors are often used for driving pumps, and are frequently used instead of steam engines for driving direct-current generators when rotary converters will not operate satisfactorily, for driving direct-current arc-lighting dynamos, for example.

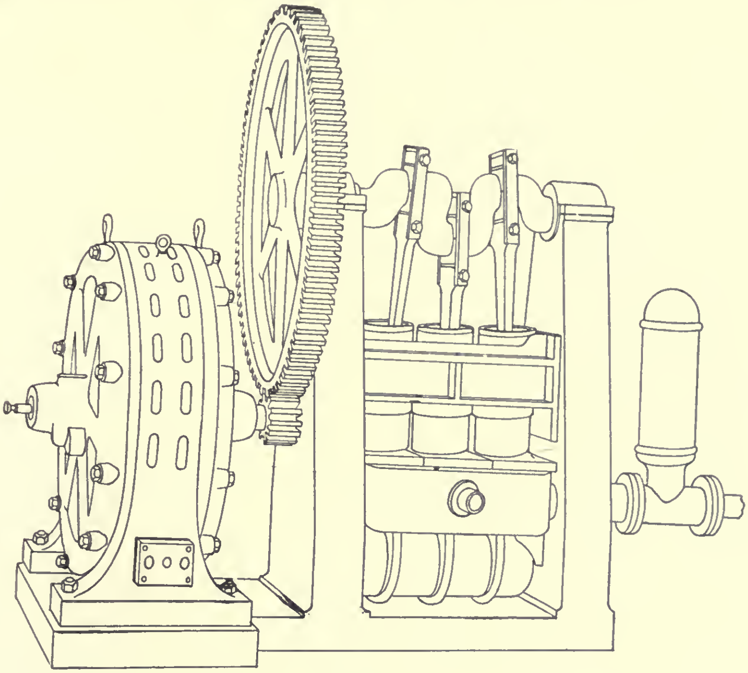


Fig. 312.

The laminations of both the stator and rotor of large induction motors are provided with ventilating ducts through which air is driven by centrifugal action. Fig. 311 shows a number of holes in the cast-iron casing through which the air flows after passing through the ventilating ducts between the laminations of the rotor and the stator.

Fig. 312 shows an induction motor driving a triplex pump. This induction motor has a starting resistance inside of the rotor, and the switch rod and knob are shown projecting from the rotor shaft at the left. (See article 139.)

Fig. 313 illustrates a very common method of installing induction motors when used for driving line shafting in shops or factories. The motor is shown bolted in an inverted position to the ceiling by means of lag screws, and is furnished with two pulleys, each belted to a different line shaft.

Since induction motors require no adjustment and practically no attention, they may be installed when direct-current motors are not suitable, with the consequent advantage of saving valuable floor space.

142. The Single-Phase Induction Motor. When an induction motor (two-phase or three-phase) is once started, and is running at full speed, all the phases but one may be disconnected from the primary member and the machine will continue to operate and carry a very considerable load, say two-thirds as much load as when all the phases are connected to the supply mains.

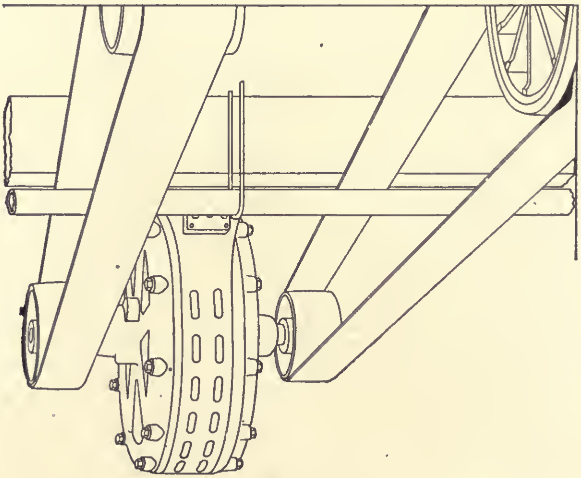


Fig. 313.

An induction motor, however, will not start when one phase only of its primary member is connected to single-phase supply mains. Therefore when it is to be driven from single-phase mains, special provision for starting must be made. An induction motor designed to operate from single-phase mains and provided with special arrangements for starting, is called a *single-phase* induction motor.

Three methods of starting single-phase motors are in general use, as follows:

(*a*) **Hand Starting.** Very small induction motors may be started by giving a vigorous pull on the belt which connects the motor to the machinery which it drives.

(*b*) **Split-Phase Starting.** When an alternating current divides between two branches of a circuit, there is a phase difference between the currents in the two branches, if the ratio of resistance to reactance is different in the two branches. This is especially true if one branch contains a condenser. Now a two-phase motor will start when the currents in the two stator circuits are less than 90° apart in phase, although the starting torque grows less and less as the phase difference of the two currents decreases. The dephasing of the two parts of a single alternating current in two dissimilar branches of a given circuit, is called *phase-splitting*, and a single-phase induction motor may be arranged to start as a two-phase motor, by splitting a single-phase current, and using the two parts of the split current exactly as one would use two genuine two-phase currents.

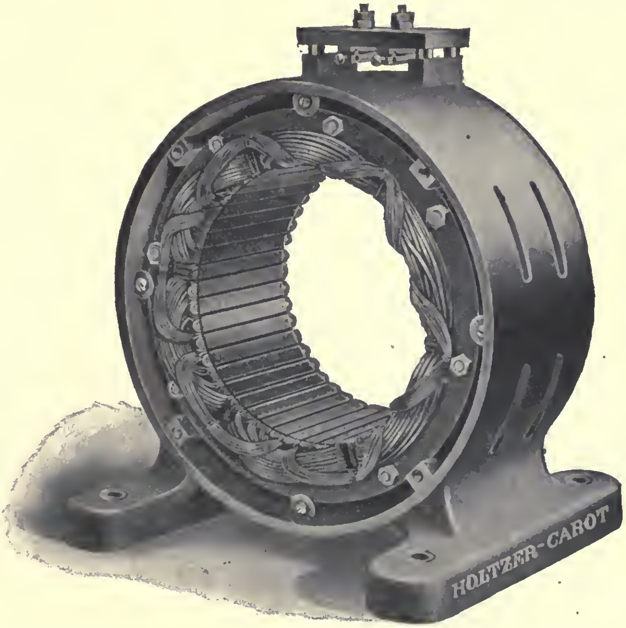


Fig. 314.

Fig. 314 shows the stator of a 2-horse-power single-phase induction motor of the Holtzer-Cabot Electric Co. One set of stator coils, the "working coils", consist of many turns of coarse wire occupying three-fourths of all the stator slots, and the other set of stator coils, the "starting coils", consist of fewer turns of fine wire occupying one-fourth of all the slots.

At starting, both sets of coils are connected to the single-phase supply mains, and the difference in the resistance and reactance in the two sets of coils splits the single-phase current supplied, sufficiently, to give a slight starting torque. This type of split-phase induction motor cannot start with any considerable load, hence the load, if it is difficult to start, should be thrown on to the motor by means of a friction clutch after the motor is running at full speed. The rotor used in the Holtzer-Cabot motor is of the squirrel-cage type.

Fig. 315 shows a $\frac{1}{2}$-horse-power single-phase induction motor made by the General Electric Co., and provided with a condenser which is connected in series with one phase (the starting coils) of the stator windings in order to give something approaching 90° phase difference between the split-phase currents. A condenser for a given volt-ampere capacity can be constructed much more cheaply for high than for low voltage. Therefore the condenser-compensator made by the General Electric Co. is provided with a small step-up transformer (auto-transformer) so that the condenser may be designed for high electromotive force.

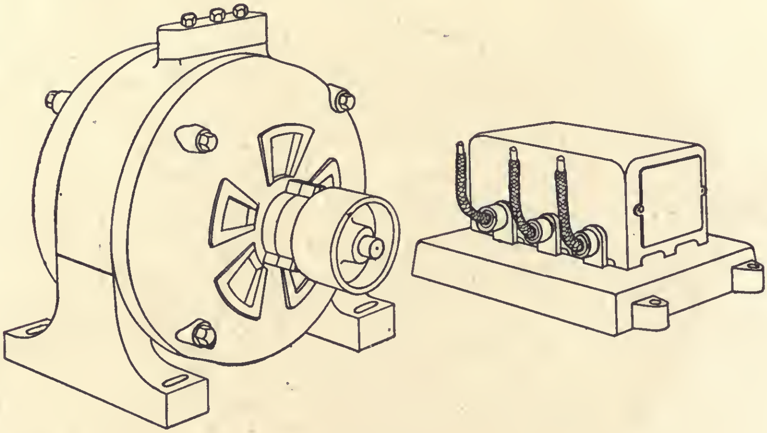
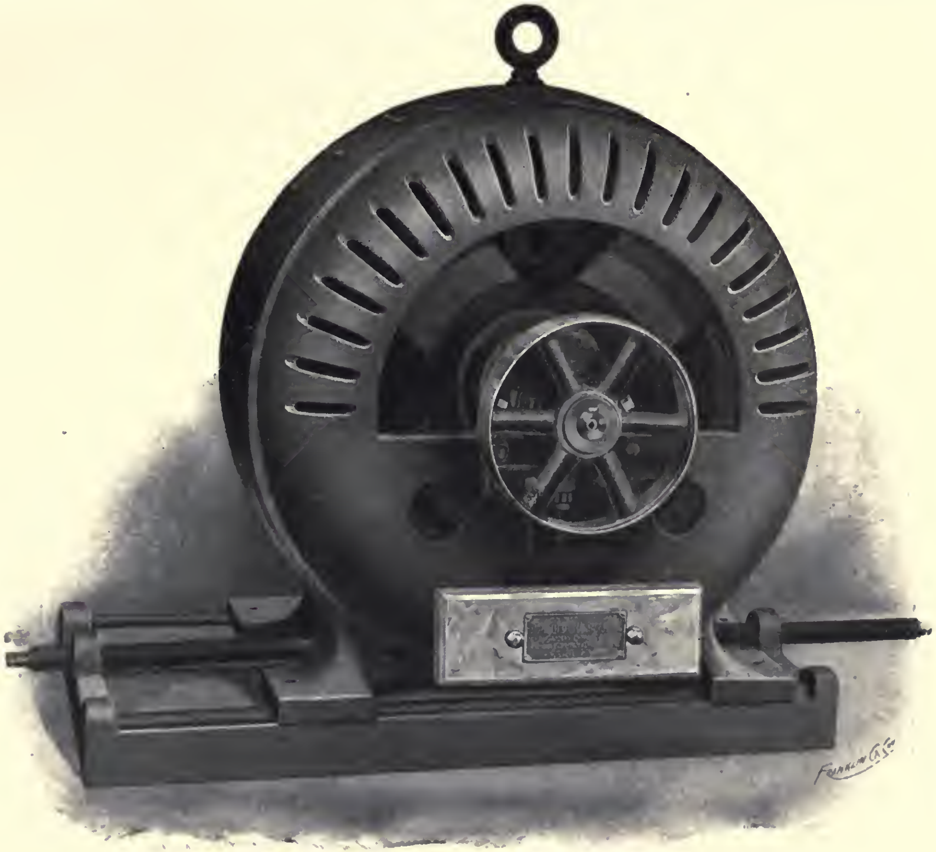


Fig. 315.

Fig. 316 shows the complete connections of the single-phase induction motor of the General Electric Co., with its condenser-compensator; the condenser is shown at *b;* *a* represents the auto-step-up-transformer. The main stator winding of the motor is



WARREN INDUCTOR TYPE ALTERNATING-CURRENT GENERATOR

Without Brushes, Commutator or Moving Wire

d e, and the starting winding *c* is connected to the middle of *d e* as shown. The motor is thus a three-phase motor at starting. When the motor reaches full speed, the starting winding *c* is disconnected, and the winding *d e* then operates as a single-phase winding

A single-phase motor will run in either direction equally well, depending only upon the direction in which it is started. Therefore the hand-started motor may be started in either direction. The direction of starting of the split-phase motor may be reversed by reversing the connections of the starting winding.

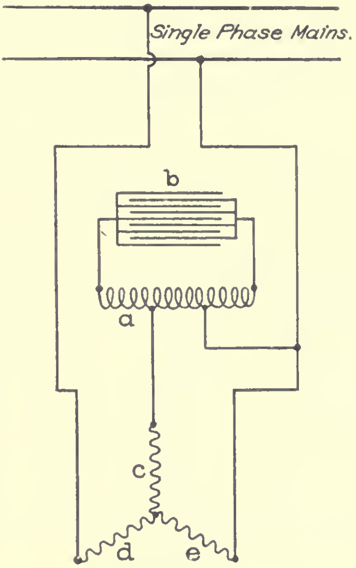


Fig. 316.

(*c*) **Repulsion Motor Starting.** If an ordinary direct-current dynamo were provided with a laminated field magnet, and if its field magnet were excited by an alternating current, currents would be induced in the armature windings by the alternating field, provided the brushes of the direct current machine were set at an angle of about 45° (for a two-pole machine) from their proper position for collecting a direct current. These currents induced in the armature would be acted upon by the alternating field so as to produce a torque which would cause the armature to rotate. A self-starting single-phase alternating-current motor constructed on this principle is called a *repulsion* motor. It is not entirely satisfactory in operation, but the repulsion-motor principle furnishes the best means for making a self-starting single-phase induction motor, that is, a motor which is arranged so that it can act as a repulsion motor while starting, and which by changing certain inside connections can be altered into an induction motor when it reaches full speed.

Fig. 317 is a general view of a single-phase induction motor arranged to start as a repulsion motor, and built by the Wagner Electric Manufacturing Co. The motor shown has a four-pole stator winding, the iron stator core being made very much like the core of an ordinary induction motor, namely in the form of a laminated ring closely surrounding the armature, and slotted on its inner face.

The armature is of the ordinary direct-current drum type provided with a disc commutator with radial commutator bars.

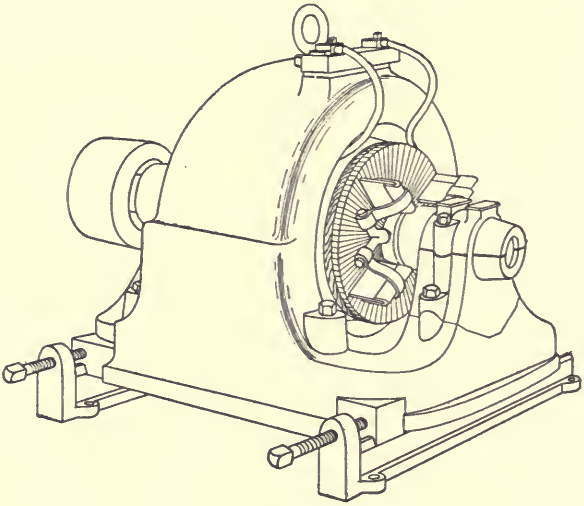


Fig. 317.

Four (for a four-pole machine) short-circuited brushes are pressed against the face of the disc-shaped commutator as shown in Fig. 317. At starting the stator winding is connected to the single-phase supply mains, and the machine starts as a repulsion motor. Inside of the armature are two governor weights V, Fig. 318, which are thrown outwards by the centrifugal force when the machine reaches full speed, thus pushing the solid copper ring K, into contact with the inner ends of the commutator bars L, and thus completely short-circuiting the armature winding. At the same time barrel I, which is pushed endwise by the governor weights and which carries the short-circuiting copper ring K, pushes the brush holder or rocker arm endwise, and lifts the brushes off the commutator.

In starting the Wagner single-phase motor, the supply voltage is usually reduced to a fractional part of the full running voltage. This is accomplished by the use of a small step-down transformer, usually an auto-transformer, in much the same way as has been explained in connection with the auto-starter or starting compensator for two-phase and three-phase induction motors.

143. The Induction Generator. An induction motor runs as a motor at a speed less than the speed of the rotating magnetism in the stator iron (synchronous speed). When the motor load is decreased, its speed approaches synchronous speed, and the intake of power from the alternating-current mains falls off more and more. If the rotor is driven by an external source of mechanical power, it may be speeded up to synchronism, in which case the intake of power becomes zero (except for core loss in the stator iron). If now the rotor is speeded *above* synchronism by the external source of power, the stator windings deliver power to the alternating-current mains, *provided the alternating-current generator remains connected to the mains to fix the frequency.* When an induction motor is so used, it is called an *induction generator.*

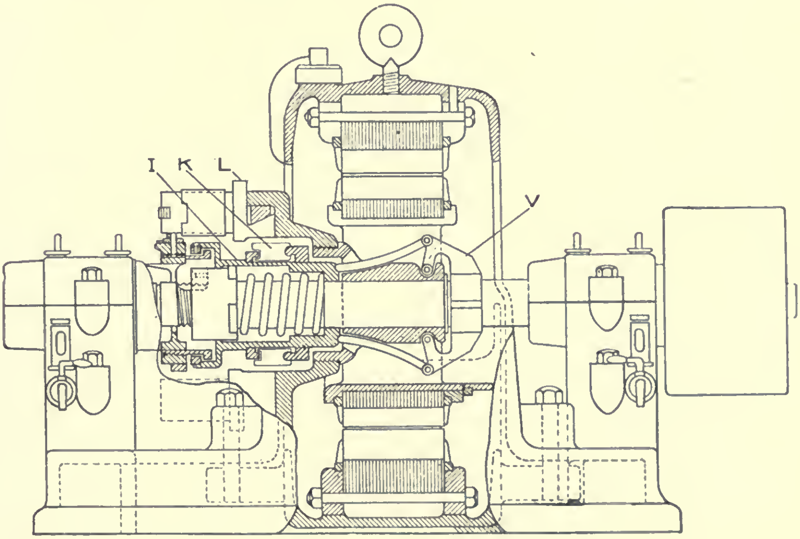


Fig. 318.

144. The Frequency Changer. An induction motor provided with a rotor having a definite winding with terminals brought out to collector rings, see Fig. 306, may be used as a so-called *frequency changer*. When the rotor stands still, the rotating stator magnetism induces electromotive forces at full frequency, that is, of the same frequency as the alternating currents supplied to the stator. If the rotor runs at one-fourth speed, let us say, the relative speed of the rotor and the stator magnetism is three-fourths of the speed of the latter, and hence electromotive forces of three-fourths full frequency are induced in the rotor windings. If the rotor is run backwards at, let us say, one-half of the speed of the stator magnetism, then the relative speed of the rotor and the stator magnetism is one and one-half times the speed of the stator magnetism, and electromotive forces of one and one-half times full frequency are induced in the rotor windings.

Examples. A certain induction motor runs at one-third synchronous speed ($n' = \frac{1}{3} n$, see article 138), then, ignoring stator losses, all of the power delivered to the stator is transmitted to the rotor, and of this total power one-third appears as mechanical power driving the rotor, and two-thirds appears as electrical power developed in the rotor windings. This electrical power, ignoring the resistance loss in the rotor windings, is delivered to the rotor collecting rings.

Furthermore, if the rotor has the same number of conductors as the stator, then the electromotive forces between collector rings are two-thirds as great as the voltages applied to the stator windings, and their frequency is two-thirds as great.

If the rotor of an induction motor is driven backwards by an external source of power at one-half synchronous speed ($n' = -\frac{1}{2} n$), then all of the electrical power delivered to the stator together with the mechanical power used for driving the rotor, appears as electrical power in the rotor windings, and the rotor voltages are one and one-half times as great in value, and one and one-half times as great in frequency as the voltages applied to the stator.

The stator current in an induction motor, or a frequency changer, is sufficient at no load to magnetize the stator. This stator current is called the no-load current of the machine. When current is taken from the rotor, an equal (and opposite) additional current is taken from the supply mains by the stator windings, *exactly as in the case of the transformer*, as explained in article 82.

The above statements are based on the assumption that the rotor windings are exactly like the stator windings, both as to the number of conductors, and as to the grouping of the conductors into separate circuits or phases. If the rotor has half as many conductors as the stator, the rotor voltages are halved and the rotor currents are doubled, other things being equal.

In alternating-current plants, designed primarily for the transmission of power, and hence using a low frequency (*e.g.*, 25 to 40 cycles per second), there is sometimes a need for a limited amount of current of a higher frequency. To meet such conditions, a frequency suitable for lighting purposes, 60 cycles or more, may be cheaply and easily obtained by means of the frequency-changer. This is essentially an induction motor as explained above, the rotor of which is driven mechanically by an auxiliary synchronous motor in a direction, usually opposite to its natural rotation. The current of lower frequency is fed to the stator windings and the current of higher frequency is taken out of the rotor windings by means of collector rings. The frequency of the motor current will depend on the speed at which the rotor is driven as explained above. Thus, if the rotor is driven at its rated speed but in a direction opposite to its natural rotation, the frequency of the current delivered by it to the collector rings will be twice the normal, or if run at half the normal speed in its natural direction, the frequency will be one-half the normal. To change a current with a frequency of 40 cycles into one of 60, the motor would be run at one-half speed in an opposite direction, while to obtain 60 cycles from a 25-cycle current, the rotor would run nearly one and one-half times the rated speed in an opposite direction.

The total power delivered to a frequency changer is partly electrical power delivered directly from the low frequency supply mains to the stator of the frequency changer, and partly mechanical power delivered by belt to the rotor of the frequency changer from the auxiliary driving motor. The power output of the frequency changer is wholly electrical and in the form of increased-frequency alternating currents from the rotor.

The electrical power delivered to the stator of the frequency changer is

$$P_e = \frac{f\,P}{f'}$$

and the mechanical power delivered by belt to the rotor of the frequency changer is

$$P_m = \frac{(f' - f)\,P}{f'}$$

where P is the total power delivered to the machine. This power, P, is nearly equal to the total power delivered by the machine at the increased frequency, being a little greater on account of power losses in the machine, f is the low frequency of the alternating currents supplied to the stator of the machine, and f' is the higher frequency of the alternating currents delivered by the rotor of the machine.

Therefore, the rotor of the frequency-changer must be designed for the total output of power at the higher frequency, and the stator of the frequency changer must be designed for the intake of the amount of power, P_e, which is supplied to it electrically.

For example, a frequency-changer rated at 100 K.W. to change a 40-cycle current to one having a frequency of 60 cycles per second would be made up as follows:

An auxiliary driving synchronous motor rated at 33.3 K.W. designed to take current from 40-cycle mains at a speed of, say, 600 r.p.m. It would therefore have eight poles. Its armature would be direct connected to the rotor of the frequency-changer which would be rated at 100 K.W. The stator of the frequency-changer would be rated at 66.7 K.W., and would be supplied with current having a frequency of 40 cycles per second. If wound for four poles, the synchronous speed (as an induction motor) of the rotor of the frequency-changer would be normally 1,200 r.p.m. But by driving the rotor (by the auxiliary synchronous motor) at a speed of 600 r.p.m. in a direction opposite to its natural rotation, the frequency of the rotor currents will be that due to an equivalent speed of 1,200 + 600 = 1,800 r.p.m.; corresponding thus to a frequency of 60 cycles per second.

For the sake of a simple illustration, the ratings as given above are based on the assumption of a 100 per cent efficiency, which, of course, on account of the unavoidable power losses, is never realized in practice.

It is evident that the frequency-changer can at the same time be designed to change the electromotive force by using a suitable number of turns in the stator and rotor windings. It can also be used to change the number of phases of the system by providing a rotor wound for a number of phases different from that of the stator. For instance, it may be designed to convert from three-phase, 6,000 volts, and 25 cycles, to two-phase, 2,500 volts, and 62.5 cycles. On account of this flexibility the frequency-changer is sometimes called a "general alternating-current transformer".

145. Comparison of Synchronous Motor and Induction Motor. To summarize the characteristic behavior in service of synchronous and induction motors, and to simplify the comparison between them, the following tabular statement in parallel columns, prepared by Mr. C. F. Scott, is given.

The induction motor chosen for comparison with the synchronous motor is of the so-called "squirrel-cage" type, started by applying a low electromotive force to the primary winding. The description following will, of course, require modification in some particulars, if the secondary is furnished with adjustable resistance, but these modifications are of minor importance and do not affect the general comparison.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
AUXILIARY APPARATUS REQUIRED.	
1. A starting motor; or, if self-starting, some form of resistance or transformer for reducing the voltage.	1. A two-way main switch with auto-transformers giving a low E.M.F. for starting. This may be at any distance from the motor.
2. An exciter, driven by the motor or otherwise, with circuits to switchboard and motor.	2. No exciter is required.
3. Rheostats for exciter and motor.	3. No field rheostats are required.
4. Instruments for indicating when field current is properly adjusted.	4. No instruments are required.
5. Main switch and exciter switches.	5. No exciter switches are required.
6. A friction clutch is required in many cases.	6. No friction clutch is required, as the motor starts its load.

CONSTRUCTION.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
1. Field winding with many turns. Liable to accident from "field discharge" if exciting current is suddenly broken; or from high E.M.F. by induction from the armature if the field circuit is open.	1. Secondary, short-circuited.
2. Collector rings and brushes.	2. No moving contacts on "squirrel cage" secondary.

NORMAL STARTING.

1. Motor is brought up to speed without load; if starting motor is used, the main motor must be brought to proper speed and "synchronized"; if self-starting, the starting devices must be cut out of circuit at the proper time.	1. Throw switch to starting and then to running position.
2. Exciter is made ready for delivering proper current and the motor field must be excited, adjustments being made until instruments give proper indication.	2. There is no exciter. (The motor is magnetized by lagging current from the generator.)
3. Load is thrown on by friction clutch or other means.	3. The motor starts its own load.

ABNORMAL-STARTING.

1. If the several operations in starting be performed improperly or in wrong order, injury may result. If a starting motor is used, the synchronizing may be attempted at an improper speed or phase; if the motor is self-starting and it is connected to the circuit without the starting devices, a large current will flow which may induce a high E.M.F. in the field circuit; if the field circuit be open, a high E.M.F. may be induced in it at other times also.	1. The only possible error is in starting with the switch in the running or full voltage position, which simply causes the motor to exert a greater torque and consume a greater current than is necessary.
2. If a load having inertia be applied by closing the friction clutch too quickly the motor may be overloaded and stopped.	2. The motor starts its own load and requires no friction clutch.
3. If motor stops owing to failure of current supply, it is not self-	3. The motor will stop if the current is cut off at the power house

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
starting when the current returns. An attendant is always required for starting.	and then start again when the current is supplied to the circuit.
STARTING AND MAXIMUM RUNNING TORQUE.	
1. The starting torque of the self-starting motor is very small and an excessive current is required for developing it. The motor starts as an induction motor, but inefficiently, as the design which is best for synchronous running is not good for starting.	1. The starting torque is adjustable and may be several times full load torque.
2. The maximum torque is several times the full load torque, and occurs at synchronous speed; below this speed the torque is very small; any condition which momentarily lowers the speed causes the motor to stop.	2. The maximum torque is usually greater than that of the synchronous motor, but it occurs at a reduced speed and there is a large torque at lower speeds.
SPEED.	
1. The motor has a single definite speed; at other speeds its torque is very small, and the current is very large.	1. The motor may be designed for a practically constant speed, with large torque at lower speeds; or for several definite speeds by changing the number of poles; or for variable speed, for cranes, elevators, hoists and the like.
CURRENT.	
1. If there is useful starting torque the current required for producing it is very great.	1. The starting current may be made proportional to the torque, and is 1½ to 2½ times that required for the same torque at high speed.
2. The running current depends upon the wave form. If the wave form of the motor and of the circuit differ, a corrective current will follow, which cannot be eliminated by adjustment of field excitation.	2. The running current is practically independent of the difference in wave form, as it has no wave form of its own.
3. The running current depends upon uniformity of alternations of the current, *i.e.*, upon the uniformity of the speed of the generator and other synchronous motors. The motors attempt to follow the generator speed exactly. If the latter pulsates,	3. The current is practically independent of fluctuations in generator speed, as there is a slip between the synchronous and the actual speed of the motor.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
the motors pulsate also; they vibrate about a mean position, "hunting" or "pumping." One motor pumping incites others. The current is increased even though the conditions may still be operative.	
4. The running current depends upon the relation between the field current (which is adjusted by the attendant) and the E.M.F. of the circuit. The main current may be made leading or lagging or theoretically it may be neither. The E.M.F. of the circuit is an element which is under the partial control of the attendants at every motor, as well as at the generator station.	4. The current is not subject to any adjustments which the motor attendant can make, nor is the E.M.F. of the circuit in any way under his control.

POWER FACTOR.

1. As the power factor is the relation between actual current and energy current, it is dependent upon wave form, hunting, and field current. Under favorable conditions, the motor may have a high power factor; under many actual conditions it may not; under some conditions the highest attainable power factor is less than that of the induction motor.	1. The power factor varies with load, but is definite and is practically independent of wave form and hunting.
2. The current may be lagging or leading.	2. The current to the motor is always lagging current.

REACTION UPON GENERATOR AND CIRCUIT.

1. The motor impresses its own wave form on the circuit.	1. The motor has no wave form to impress upon the circuit; its tendency is to smooth out irregularities in a wave not a sine.
2. A motor may augment the fluctuations in generator speed by the oscillation of its own armature. One motor may increase the disturbance in the circuit so as to interfere with other motors not otherwise seriously affected.	2. The motor has a damping action upon fluctuations in frequency; in some cases a synchronous motor which hunts may run smoothly when an induction motor is connected to the same circuit.
3. As the current may be either lagging or leading, the drop in E.M.F. in the generator, and be-	3. The drop in E.M.F. is always greater than would be caused by non-inductive load.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
tween generator and motor may be either more or less than that which could be caused by a non-inductive load or by an induction motor.	
4. If a short-circuit occurs in the transmission system, the motor acts as a generator, which thereby greatly increases the current and the intensity of the short-circuit.	4. The motor does not generate current when there is a short-circuit.
5. If the circuit is opened, either by a switch, a circuit breaker, a fuse, or the breaking of the line, the motor speed falls, its E.M.F. is no longer in phase with that of the circuit; the two are thereby added, thus doubling the normal E.M.F. and bringing increased strains on the insulation and the opening devices.	5. The motor does not generate E.M.F when it is disconnected from the circuit.

CAUSES WHICH MAY ACCIDENTALLY STOP A MOTOR.

1. Momentary lowering of E.M.F. caused by short circuit on the line, or by accident at another motor, or by error in synchronizing a generator, or by the "switching over" of the motor from one circuit to another, is apt to cause the motor, particularly if carrying load, to fall from synchronism and stop.	1. Momentary lowering of E.M.F. causes momentary decrease in speed.
2. A heavy load, even momentary, may exceed the limiting torque and cause the motor to drop from synchronism, even though the load be removed immediately. The connection between generator and motor is rigid.	2. An excessive load receives the stored energy of the motor and of the load itself as the motor speed falls; when the excess load is removed the motor speed increases again. The connection between generator and motor is elastic.
3. If the generator speed suddenly increases, a motor carrying a load having inertia may be unable to increase its speed quickly without exceeding the limiting torque, which will cause the motor to stop.	3. The motor readily follows changes in generator speed.

SUMMARY.

1. The motor is an *active* element in the system; it acts as a generator in impressing its own wave form, its E.M.F. and its fluctua-	1. The motor is a *passive* element in the system. Each motor attends to its own work and does not try to run the system.

SYNCHRONOUS MOTOR.	INDUCTION MOTOR.
tions upon the circuit. These fluctuations may be caused by an intermittent load.	
2. The motor is a sensitive element in the system. Its successful operation is dependent upon a proper relation between the design of the motor itself and of other machines in the system. Its successful operation also depends upon the proper adjustment and freedom from speed fluctuation in generators and other motors. It is liable to momentary variations from normal conditions, such as a sudden overload and sudden increase of generator speed or a momentary fall in E.M.F.	2. The motor is not sensitive to differences in the design of other apparatus operating on the same system.
3. The motor requires skill and care on the part of the attendant for starting, for readjusting and for keeping the various brushes and auxiliary apparatus in condition.	3. No experience and electrical skill are required of the attendant and there is little or nothing to get out of order either through carelessness or design.
4. The power factor is under the control of the operator and the current may be made leading or lagging. Instruments are necessary in order that proper adjustments may be made by the attendant.	4. The motor has a definite power factor, depending upon the load; the out-of-phase current does not vary greatly at different loads. The changing load, therefore, has comparatively little effect upon the drop in voltage and in regular service there is little liability that the motor will disturb the E.M.F. of the circuit.
5. The motor and its operation are complex and involve many possibilities of accident.	5. The motor and its operation are simple and reliable.

The synchronous motor is obviously not suitable for general distribution of power, owing particularly to its lack of starting torque, the skill required in attendance, and the liability of the motor to stop if the conditions become abnormal. These objectionable features, however, are of much less importance when motors are installed in substations or are of sufficiently large size to justify an attendant.

The characteristic of the synchronous motor which may be particularly advantageous is the fact that the power factor of the current can be varied and that the current may be made leading.

MOTOR-GENERATORS.

146a. Direct current may be obtained from an alternating current circuit or circuits by the rotary converter or by a motor-generator. A motor-generator for alternating-current work consists of an alternating-current motor driving one or more direct-current generators. The motor may be of the induction or of the synchronous type. In either case the motor is usually mounted on the same base with, and mechanically coupled to, the generator.

A motor-generator employing a synchronous motor does not seem to possess any essential advantages over the rotary converter, except in some cases where the independent control of the direct-current voltage is desired. The use of the synchronous motor does not remove the objections to the rotary converter which are based on the fact that it is a synchronous machine.

A motor-generator employing an induction motor has the advantage of using induction instead of synchronous apparatus, thereby securing many of the advantages summarized above in the comparison between synchronous and induction motors.

Circuits which are supplied by alternating-current generators in which the speed has a rapid and periodic fluctuation, or in which for any other reason the conditions are such as to cause "hunting" in synchronous machines, may, however, satisfactorily operate an induction motor driving a generator. The various characteristics of the induction motor under emergency conditions, such as a sudden overload, momentary interruption or lowering of the voltage of the supply circuit, may cause little or no inconvenience if the induction motor is used, whereas it might cause serious interruption to a rotary converter or a synchronous motor. The induction motor driving a generator is also to be preferred where the size of the units is quite small and the attendance is unskilled. The armature for the induction motor should in general be of the squirrel-cage type as the required starting torque does not exceed 20% of full-load torque, and the required starting torque can be obtained with about full-load current.

The rotary converter, like the synchronous motor, is not suitable for general distribution in small units. It has the advantage over the motor-generator in point of cost, there being but one machine instead of two; in point of efficiency, there being the loss in one machine instead of two; and in its effect upon the voltage of the transmission system as a whole, as it may be compounded to overcome the drop which would otherwise occur in generator and transmission circuit.

On the other hand, the electromotive force of the direct current delivered by the converter has a more or less fixed relation to the electromotive force of the alternating currents supplied; whereas the electromotive force of a motor-driven generator is independent of the electromotive force of the supply circuit, and it may be adjusted or compounded as may be desired. In practice, however, it is found that the voltage delivered by a rotary converter can be satisfactorily adjusted and controlled by regulating devices or by compounding, so that usually the close relation between the electromotive forces at the two ends of the converter is not disadvantageous, provided the electromotive force of the supply circuit is reasonably constant. This statement applies to those cases where a practically constant direct-current voltage is desired. There are, of course, special cases, in which the voltage is to be adjusted over a wide range, or where, for other reasons, the motor-generator is to be preferred. In many cases the motor may be operated without requiring step-down transformers, whereas they would be necessary with rotary converters.

Motor-generator sets are often used in central stations in connection with arc-lighting service. In these cases alternating-current motors are used for driving arc-lighting generators, as in the large plant of the Buffalo General Electric Company. They are also used in some places for supplying three-wire direct-current lighting circuits from alternating-current mains.

Motor-generators are often used in central stations for furnishing direct current to the field-magnet windings of alternators, the direct-current generator part of the set acting as the exciter for one or more large alternators. The alternating current supplied to the (synchronous or induction) motor end of the motor-generator set, is taken from the main station bus-bars, and stepped-down by means of reducing transformers to a safe voltage.

Examples of this use of motor-generator sets are to be found in the immense power stations of the Manhattan Railway Co., and the Metropolitan Railway Co., of New York City, and in many other places.

Another use for motor-generators is as frequency changers (or converters). In such cases they are used for transforming an alternating current of one frequency to another alternating current of higher or lower frequency, usually the former. The current may be transformed from three-phase to two-phase (or *vice versa*) at the same time. Thus it might be required to supply a two-phase 60-cycle lighting system from a 25-cycle three-phase transmission system, with or without change of voltage.

A motor-generator set built by the General Electric Company is shown in Fig. 319. It consists of a combination of three distinct machines, all mechanically coupled to the same shaft, viz.:

1. A three-phase synchronous motor, of the revolving-field type.
2. A three-phase alternator also of the revolving-field type.
3. A direct-current generator acting as an exciter for the fields of both the alternator and the synchronous motor.

SUMMARY OF DATA FOR FIG. 319.

	Synchronous Motor	Alternator	Exciter
No. of poles	8	12	10
Rated output (K.W.)	275	250	10
Speed	570	570	570
Frequency	38	57	—
Volts	—	—	60

This particular motor-generator set is designed to be used as a frequency-changer to change from 38 to 57 cycles per second. The three-phase alternating currents having a frequency of 38 cycles per second are led into the stationary armature terminals of the synchronous motor (shown next to the pulley in Fig. 319). The motor having eight field poles, its synchronous speed is 570 r.p.m.; and since both the alternator and the exciter are coupled to the same shaft, all the machines run at 570 r.p.m.

The alternator having 12 field poles, the frequency of its induced electromotive forces is 57 cycles per second. Hence the three-phase alternating electromotive forces induced in the stationary armature of the alternator have a frequency 50% higher than the alternating currents supplied to the driving synchronous motor.

Fig. 320 is a view of a motor-generator set built by the General Electric Co. It consists of a compound-wound direct-current

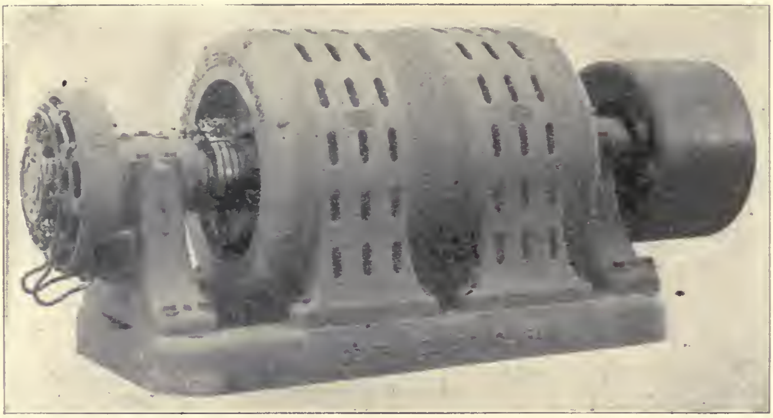


Fig. 319.

generator driven by an induction motor, both machines being mounted on the same bed-plate and having a common shaft.

Fig. 321 shows two motor-generator sets, each consisting of two Brush arc-light dynamos directly coupled to an induction motor. In some of the stations of the Brooklyn Edison Co., Brush arc-light dynamos are driven in pairs by being directly coupled to three-phase, 25-cycle synchronous motors. The constancy of the

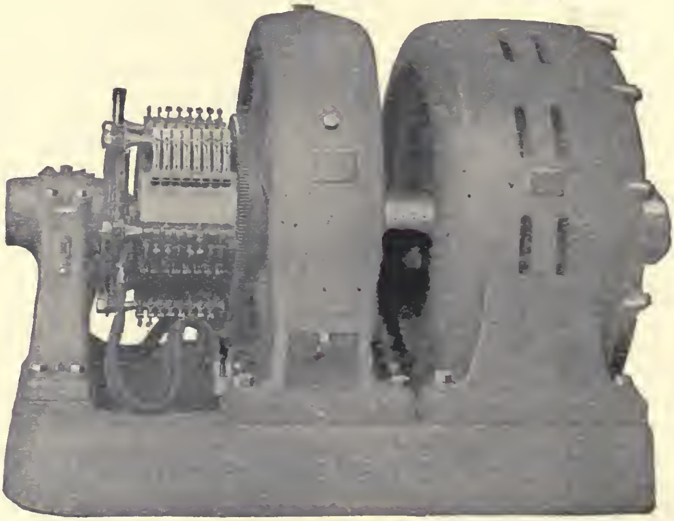
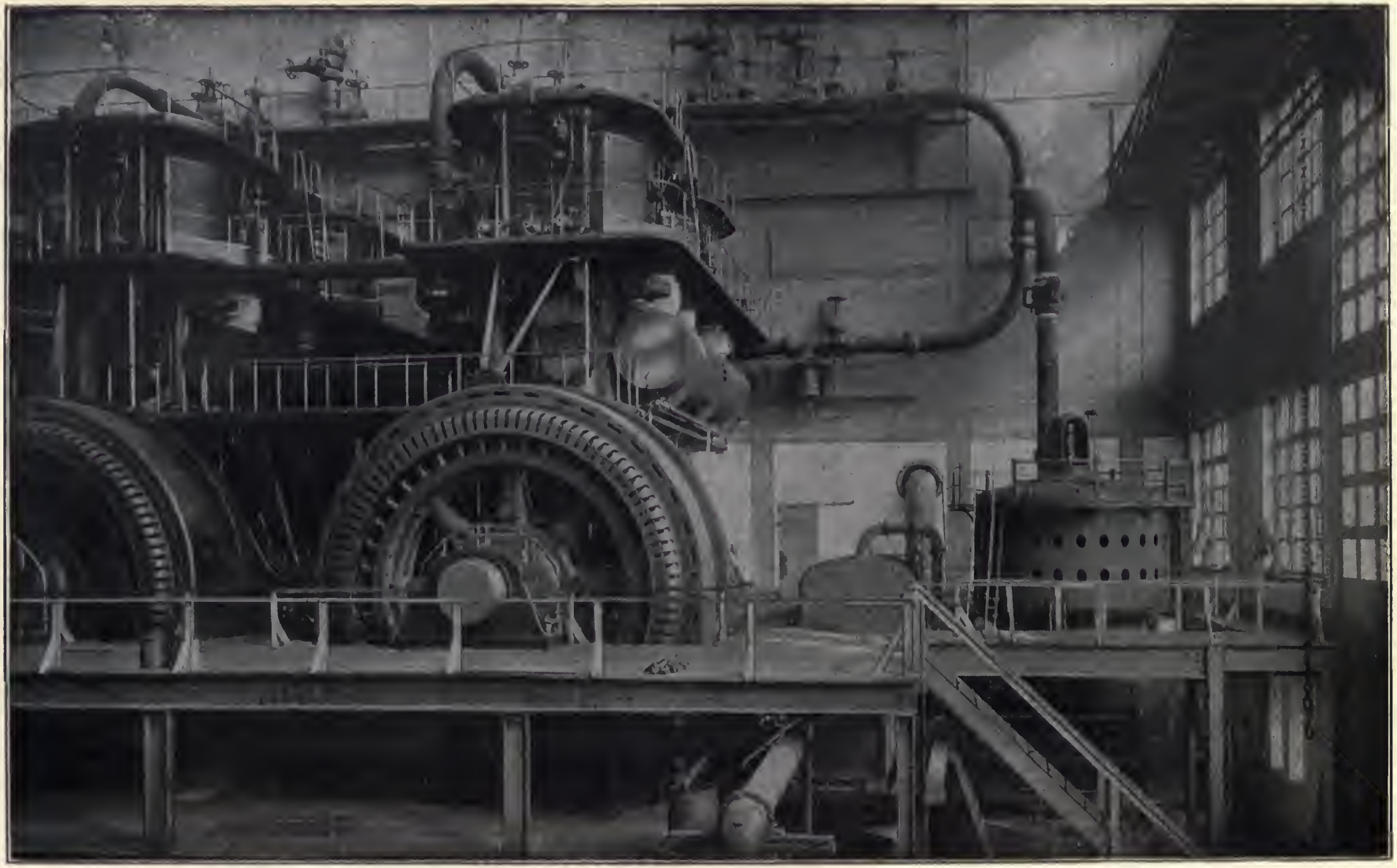


Fig. 320.



THE STEAM TURBINE *vs.* THE STEAM ENGINE

The Curtis steam turbine, with generator, seen in the right background, is rated at 5,000 kw. 6,600 volts, at 500 r. p. m., whereas each of the enormous generators connected to vertical compound engines, shown at the left, has a rated capacity of only 3,500 kw. View taken in Waterside Station of the New York Edison Company, New York City.

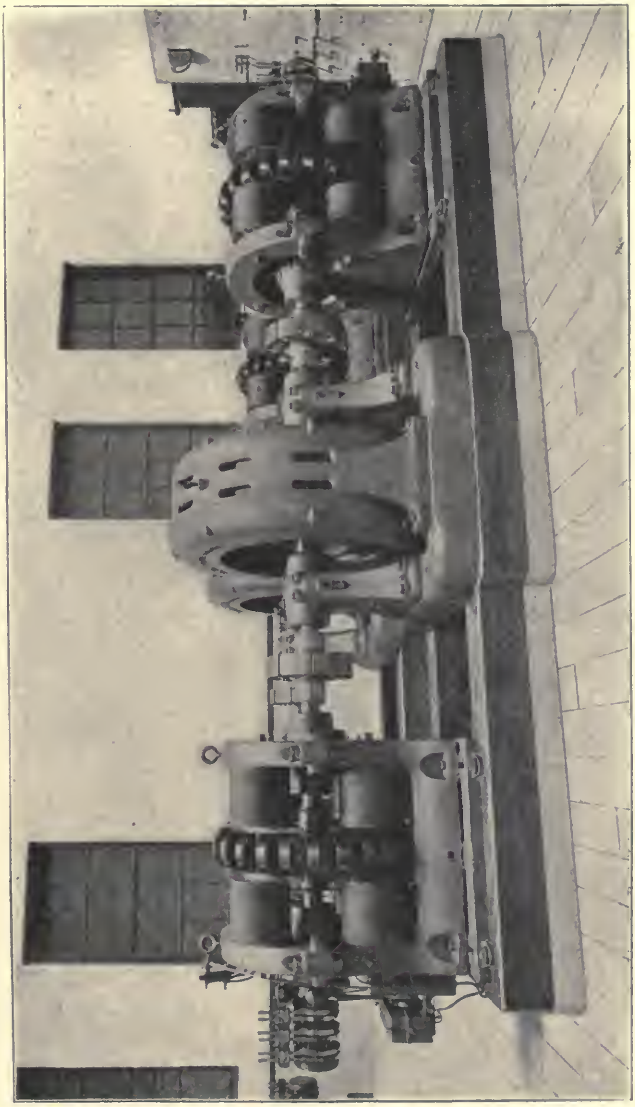


Fig. 321.

speed of synchronous motors makes them especially well suited to driving electric generators.

Fig. 322 shows an 800-horse-power Bullock two-phase synchronous motor directly coupled to two direct-current generators, all three machines being mounted on the same bed-plate.

INDUCTION MOTOR TESTS.

146b Heat Test. The heat test on induction motors is usually carried out by connecting the terminals of the stator windings to mains of the proper voltage and frequency, and taking rated full-load mechanical power from the rotor until a constant temperature has been reached. Then the motor is shut down, and the following temperatures taken:

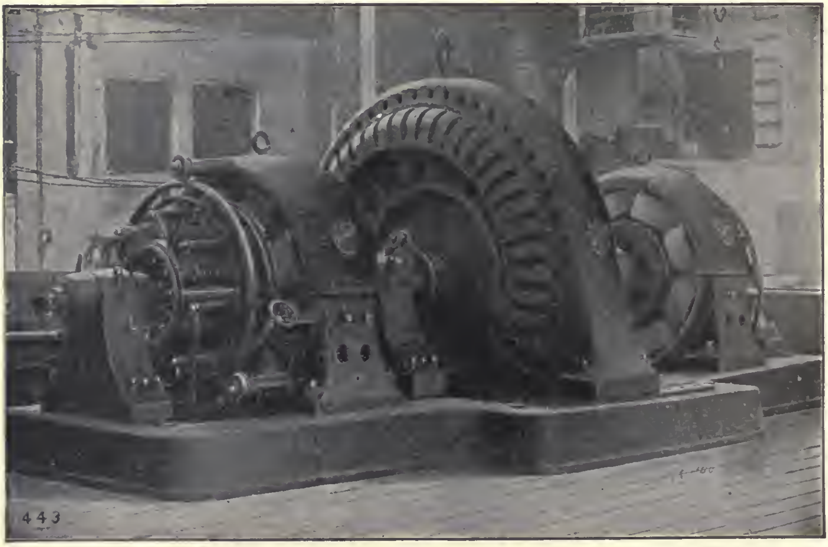


Fig. 322.

Armature laminations.
Armature conductors.
Field conductors.
Field laminations.
Frame.
Bearings.
Room.

If the motor is small, the mechanical power output may be absorbed by a brake. For large power motors, however, a brake becomes troublesome. In any case, the most convenient way to measure the power, is to belt to the motor a direct-current separately-excited generator, whose losses can be easily determined, and measure the output of this generator. The output of the motor is equal to the output of the generator plus the losses in the generator. The losses in the generator are: the I^2R loss in the armature, brush and bearing friction, and windage loss, and the core loss due to hysteresis and eddy currents.

The field being separately excited, the field loss need not be considered. The field current must, however, be kept constant.

During the heat run, the following observations are regularly recorded:

MOTOR.			GENERATOR.			
Volts.	Amperes.	Speed.	Volts.	Amperes Armature.	Amperes Field.	Speed.

Now the I^2R loss in the generator armature can be calculated from the current flowing, and the resistance of the armature.

To determine the stray power losses (equal to all the losses except I^2R) proceed as follows:

Disconnect the motor from the alternating-current mains, and run the combination of motor and generator from the direct-current end, at the same speed as that recorded during the run, the direct-current machine being now used as a motor. Its field is excited to the same value that it had during the run. The speed is adjusted to the right value by varying the voltage supplied to the direct-current machine used as a motor. When the speed is correct, record the amperes and volts taken by the direct-current machine. Next the belt is thrown off, and the voltage supplied to the armature terminals of the direct-current motor is adjusted until proper speed is attained, the field current remaining as before, and the input of power is again recorded.

Let W_1 = the watts input to the direct-current motor with the belt off;

W_2 = watts at same speed to drive both machines with belt on;

C = core loss of direct-current machine;

F = friction of direct-current machine without belt;

F_1 = friction of induction motor without belt;

f = increase of bearing friction of direct-current machine due to belt tension;

f_1 = increase of friction of bearings of induction motor due to belt tension.

Then $W_1 = C + F$ (1)

and $$W_2 = C + F + F_1 + f_1 + f \qquad (2)$$

Subtracting (1) from (2) we get

$$W_2 - W_1 = F_1 + f_1 + f$$

or $$W_2 - W_1 - F_1 = f + f_1$$

Now, since the two machines are of about the same size, we may assume that the increase in friction of each, due to belt tension, is the same, so that:

$$f = f_1 = \frac{W_2 - W_1 - F_1}{2}$$

But F_1, the friction of the induction motor, can be determined as described under core-loss test. Hence we have the following expression for the stray-power loss of the generator:

$$\text{Stray-power loss} = W_1 + \frac{W_1 - W_2 - F_1}{2}$$

Total output of motor = Stray power loss of generator + EI + I^2R.

This expression gives an exact method of determining the output of any kind of motor, by using a direct-current generator as a load. If F_1 is unknown, we may neglect the increase of bearing friction due to belt tension, giving results sufficiently accurate for a heat run.

147. Breakdown Test. The breakdown test, as in the case of a synchronous motor, is to determine the maximum output of the motor, that is, the load which will cause the motor to "break down" and stop. To make this test the load on the motor is increased, until the motor breaks down, the maximum output being noted. It is essential that the alternating currents be supplied to the motor at normal voltage. As the torque, and therefore the maximum output, varies as the square of the voltage, the results obtained by this test will not be accurate unless the voltages applied to the stator windings are kept constantly at normal value. If for any reason it is impossible to load the motor to the breakdown point, the voltage may be reduced, and the maximum load at normal voltage may be calculated from the value obtained at the reduced voltage by multiplying the observed maximum load by $\left(\frac{\text{normal voltage}}{\text{reduced voltage}}\right)^2$

If, for example, an induction motor rated at 50 H.P. gives a maximum output of 25 H.P. at one-half its rated voltage, its maximum output at normal voltage would be approximately 100 H.P.

The most convenient way to load the motor in the above test is to belt it to a direct-current generator as previously explained. To determine the output of the induction motor, from observations on the direct-current generator, proceed in the same manner as described under heat run.

In commercial work it is not customary to run this test to the breakdown point. The usual method is to find out if the motor will stand 50% overload without breaking down. When, however, it is desired to obtain a full set of data on a machine, the test is carried to the breakdown point.

148. Starting Torque Test. The stationary or starting torque developed by a motor determines the amount of load under which it will start. To perform this test a brake is clamped to the pulley as shown in Fig. 323. A is the center of the pulley; B is the point of suspension of the brake arm from the spring dynamometer S; C is a reference pointer, carried on a standard, on a horizontal line through the center of the pulley. The spring S will measure the tangential force exerted by the motor at a radius AB when B has moved down to the point C, and the spring dynamometer S is suspended vertically.

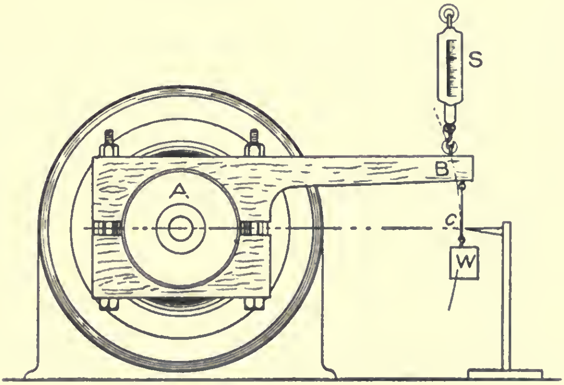


Fig. 323.

The reading of S will be affected by the friction in the motor bearings. The following procedure will eliminate this error: Fasten to the brake arm a weight W, sufficient to overcome the friction of the bearings, so that the arm if left unsupported, will always be carried downward by its weight. By slowly raising and lowering the brake arm by means of the cord which supports the spring dynamometer S (no current passing through the motor), we get two different readings of S when B passes the point C. While the arm is being raised the friction in the bearings acts in the *same* direction as the weight W. Second, as B passes C, while the arm is being lowered, the friction of the bearing acts *against* the direction of the pull due to W.

Let W = pull exerted by the weight of the brake arm and weight;
F = friction of the bearings;
a = scale reading when arm is being raised;
b = scale reading when arm is being lowered;

Then $W + F = a$
and $W - F = b$
or $W = \frac{a + b}{2}$

Let T be the force exerted by allowing the current to act on the motor, this force being in the same direction as W. Then with current flowing in the motor let:

c = scale reading while arm is being raised.
d = scale reading while arm is being lowered.

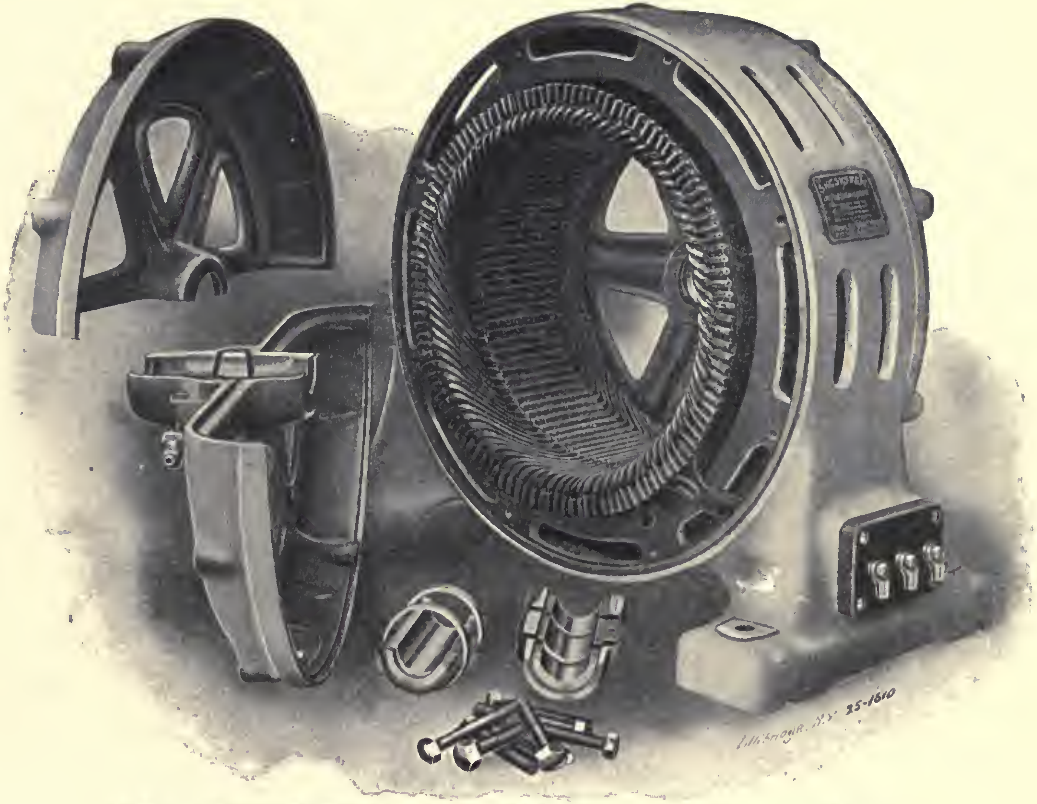
Then $T + W + F = c$
and $T + W - F = d$
or $T + W = \frac{c + d}{2}$

But from above we have $W = \frac{a + b}{2}$,
substituting this value of W we have

$$T = \frac{c + d}{2} - \frac{a + b}{2}$$

By this method both the weight of the brake arm and the friction of rest in the bearings are eliminated.

To carry out this test, this set of observations is repeated for as many values of the current in the motor, as desired. The current should range at least from one-half to twice the normal full-load current. To obtain the desired current, the voltage across the motor terminals must be adjusted.



S.K.C. INDUCTION MOTOR, WITH ARMATURE OR SECONDARY REMOVED,

Showing Field or Primary Winding and Bearings in the End Frames

ALTERNATING CURRENT MACHINERY.

PART VI.

149. Core Loss Test. The core loss of an induction motor cannot be measured by the method used in the case of a synchronous motor or alternating-current generator, namely, by driving it by a direct-current motor and observing the motor input for various voltages generated, since an induction machine will not generate electromotive force unless it is connected to the mains. If it is connected to the mains, the mains may supply power to it, and hence the power supplied by the direct-current motor is not the total power delivered to the machine.

The core loss is measured in the same manner as in the case of a transformer, namely, by connecting it to the alternating-current mains at normal voltage and frequency, and measuring the watts input at no-load. There is this difference, however, between the case of the transformer and that of an induction motor, that, whereas in the former the power is practically all used up as core loss, in the latter, part of the power goes to supply the friction and windage losses of the motor, and the appreciable I^2R loss in the stator windings.

When an induction motor is run at no-load, the speed remains practically constant as the voltage is reduced, until the motor breaks down. The power input to the motor (at no-load) at any voltage consists of the core loss at that voltage plus the friction and windage loss plus the I^2R loss. But the friction and windage loss is nearly constant at constant speed, therefore the watts input to the motor at various voltages consist in part of the constant friction and windage loss, and in part of the variable core loss. Such a series of observations on a one-H.P. 550-volt 3-phase motor is shown plotted in Fig. 324. The voltage can be reduced to the point at which the motor breaks down; beyond this we cannot go. As the ordinates on this curve are equal to the sum of a constant and a variable part, and since at zero voltage the variable part becomes zero, it follows that if we prolong the curve as shown in the dotted portion until it crosses the axis of watts (that is for zero volts), the value intercepted on the axis of watts may be considered, without much error, to be the constant part of the watts, namely, the friction and windage loss. Thus in Fig. 324, 26 watts represents the power lost due to friction and windage in the case of the induction motor above mentioned. The sum of the core loss, friction losses, and I^2R loss at normal voltage (viz., 550 volts) is found from the curve to be 109 watts. For each observed value of the volts and the watts, the current input per phase to the stator windings must be recorded. Then, the resistance of the stator windings having been measured, the I^2R loss corresponding to any given voltage can be calculated. To obtain the core loss corresponding to any voltage, we must therefore subtract the constant friction losses plus the I^2R loss in the stator windings from the total observed input to the motor (when running unloaded).

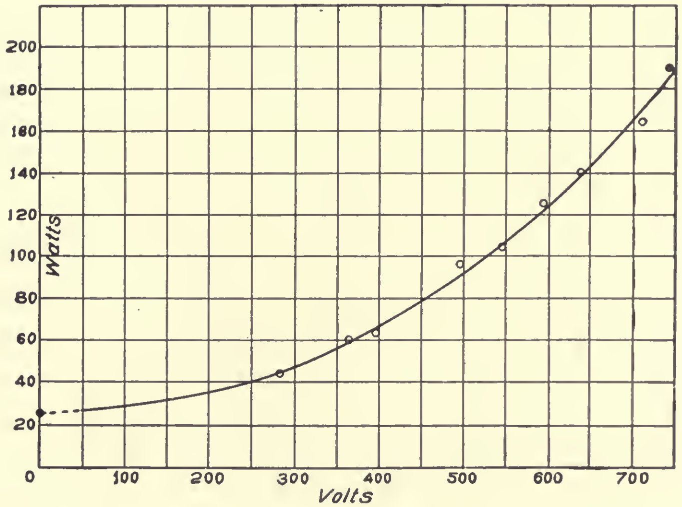


Fig. 324.

In the case of the one horse-power induction motor under consideration, the current input per phase was measured and found to be 0.655 amperes, when the voltage between supply mains was 550 volts. The resistance per phase was also measured and found to be 15.5 ohms. The total I^2R loss was therefore, $3 \times 0.665^2 \times 15.5 = 20$ watts.

The core loss at normal voltage is therefore equal to

$$109 - 26 - 20 = 63 \text{ watts.}$$

150. Impedance Test. This test is carried out in the same manner as the core-loss test. The motor is connected to the alternating-current supply mains and the amperes flowing, the watts input, and the volts at the terminals of the motor are measured, the watts, of course, being measured by watt-meters. In this test, however, the motor is not allowed to run free, but its armature is blocked to prevent it from turning. Instead of supplying normal voltage to the motor, the voltage is raised carefully until the ammeters show about one-third to one-half of the full-load current. The motor must be supplied with current at normal frequency. The following observations should be recorded:

Amperes in each line.
Volts for each phase.
Total watts.

The observations are repeated with increasing value of the voltages, until the current has reached more than twice the full-load value. Fig. 325 shows curves of observations taken in this way for the one-H.P. 550-volt, three-phase motor referred to above. This motor takes one ampere of current per phase at full-load. The two curves are plotted with current and volts, and with watts and volts as ordinates and abscissas, respectively. The former curve is the straight line.

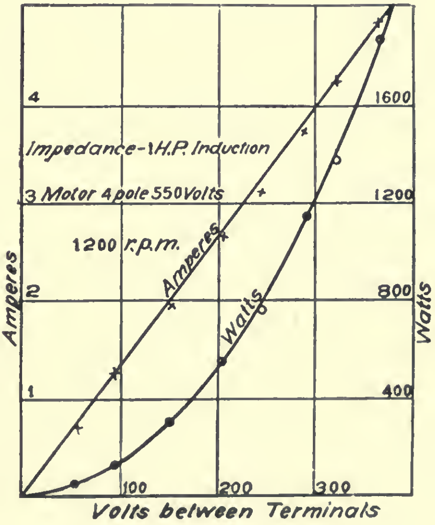


Fig. 325

Since for full-load current with the armature standing still, the voltage applied to the terminals of the motor is very low, the number of watts supplied to overcome core loss is very low. Practically, all the watts supplied are used up in heating the conductors of the stator and rotor. The watts input, therefore, for normal rated full-load current with rotor blocked, may be taken as a measure of the total I^2R losses (primary and secondary) of the entire machine at full-load. For the motor for which the curves are shown, the I^2R losses at full-load current are equal to 100 watts.

151. Calculation of Efficiency. As in the case of the machines previously considered, the efficiency of an induction motor, at a given load is equal to the output, divided by the output plus the losses, at that load. All the losses can be determined from the core-loss test and the impedance test; the core loss and friction and windage losses being determined from the former, and the copper losses from the latter. For the three-phase, one-H.P. motor above mentioned, the losses at full load are as follows:

Friction and Windage,	26 watts
Core loss,	63 watts
Copper loss (I^2R),	100 watts
Total losses,	= 189 watts.

Therefore the efficiency at one horse-power output is,

$$\frac{746}{746 + 189} = 79.8\%.$$

The efficiency of large machines is generally calculated in this way. For smaller machines it is more usual to determine the efficiency by actually measuring input and output. The reason for this is that the actual losses occurring in the motor when it is loaded, are different from the values as calculated from results of tests at no-load. The differences between these calculated and actual losses are comparatively large in a small machine.

To test the efficiency by measuring the total input and output, the most convenient method is to belt the motor to a direct-current generator, measuring the output of the generator, and the input to the motor. The output of the motor is, of course, equal to the output of the generator plus the generator losses. The losses of the generator may be calculated as described under the heat test.

The output and input of the motor are measured for various loads successively from a very small load to perhaps 50% overload, so that a curve may be constructed showing the relations between efficiency and load. The losses of the generator must be determined at each speed occurring in the series of observations, because the generator losses vary with the speed.

152. *Slip Test.* The slip at a given load on the motor is the ratio

$$\frac{n - n'}{n}$$

where n is the synchronous speed of the motor, and n' is the speed under the given load. Slip is usually expressed in per cent, in which case

$$\text{per cent slip} = \frac{n - n'}{n} \times 100$$

The synchronous speed in revolutions per second is equal to $\frac{2f}{p}$, where f is the frequency of the alternating currents supplied to the stator, and p is the number of "poles" of stator magnetism, NS NS in Figs. 293, 294, and 295. The slip is independent of the number of phases.

The speed of the motor at zero-load is very nearly equal to the synchronous speed, and where f and p are not known, the zero-load speed may be used for n without great error.

The determination of the slip of an induction motor at full-load with full rated voltage applied to the stator windings, is an important test. This slip may be determined by observing, by means of a speed counter or tachometer, the speed n' of the motor under full load and with full rated voltage. If p and f are known, the slip may be calculated as explained above.

Various methods have been proposed for measuring the slip of an induction motor directly. A simple piece of apparatus for determining the slip directly, consists of a black disc with p white radial lines painted upon it, where p is the number of poles of the motor. This disc is attached to the motor pulley. If, when the motor is running, the disc is illuminated by an alternating-current arc lamp supplied with current from the same mains as the motor, the white lines on the disc would appear stationary if the motor were running in synchronism. If the motor were below synchronism, the disc would appear to rotate with a speed equal to the difference between the synchronous and actual speed. Thus the slip can be measured directly by counting the apparent revolutions per minute of the disc.

For example, the synchronous speed of the one-H.P. motor considered above, is 1,200 r.p.m. In applying the above test the disc made 70 apparent revolutions per minute when the motor was running at full load and therefore the slip at full-load was

$$\frac{70}{1200}; \text{ or } 5.83\%.$$

153. Performance Curves of an Induction Motor. Fig. 326 shows the performance curves of a 175-H.P. three-phase, twelve-pole induction motor having a synchronous speed of 600 r.p.m., when supplied with three-phase currents at 550 volts and 60 cycles per second. The abscissas of all the curves are *horse-power output.* The drooping of all the curves in the region between 340 and 360 horse-power shows that the maximum power which the machine can develop is about 350 horse-power. There are three scales of ordinates, namely, "amperes input," "per cent," and "pounds torque". The ordinates of the curve marked "synchronism" are measured on the per cent scale, and they represent the speeds in per cent of the synchronous speed at the various loads.

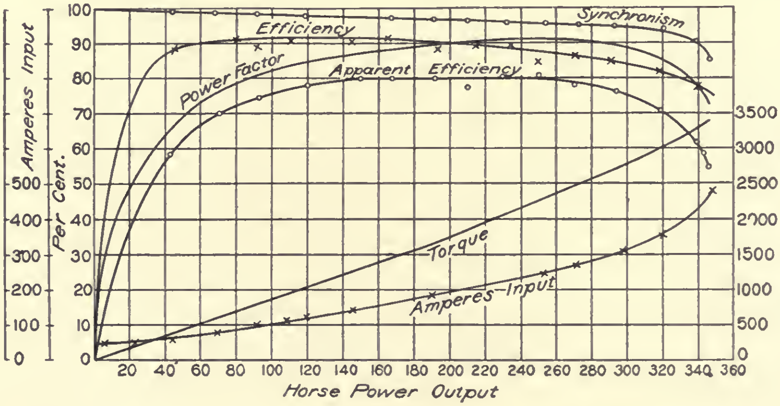


Fig. 326.

The ordinates of the curve marked "amperes input" give the amperes input per phase at the various loads.

The ordinates of the curve marked "torque" are measured on the pounds torque scale, and they represent the torque developed by the motor at various loads, these torques being expressed in pounds of force acting at one foot radius, that is, in pound-feet.

The ordinates of the curves marked "efficiency", "apparent efficiency", and "power factor", are measured on the per cent scale, and they represent these quantities at the various loads. The efficiency is, of course, the ratio, $\frac{output}{input}$. The power factor is the factor by which the product of volts times amperes must be multiplied to give the true input of power per phase.

The product volts times amperes is called the *apparent power* delivered by an alternating current generator, and the *apparent efficiency* of an induction motor is the ratio: *output* divided by the *apparent power delivered.* The apparent efficiency is thus equal to the true efficiency multiplied by the power factor.

The relation between the three factors, efficiency, power factor, and apparent efficiency, will be made clear by the following equations, each based on definition.

$$\text{Efficiency} = \frac{\text{useful output}}{\text{actual input}}$$

$$\text{Power factor} = \frac{\text{actual input}}{\text{apparent input}}$$

$$\text{Apparent efficiency} = \frac{\text{useful output}}{\text{apparent input}}$$

From the above three equations, it is evident that

$$\text{Apparent efficiency} = \text{Efficiency} \times \text{Power factor.}$$

When the output of a motor under a given load is measured mechanically by observing the useful torque developed at the armature shaft, and the speed of the armature, we have

$$\text{Useful output} = \frac{2\pi n' \mathrm{T}}{33000} \text{ horse-power}$$
$$= 0.142\, n' \mathrm{T} \text{ watts}$$

where n' is the speed of the armature in revolutions per minute;

T is the *useful* torque in pound-feet, developed by the armature.

The actual input to a three-phase alternating-current motor of the induction type is

$$\sqrt{3} \cdot E \cdot I \cdot P \text{ watts}$$

where E is the electromotive force (effective value) applied between any two of the stator terminals;

I is the current (effective value) in any one of the leads supplying the stator windings;

P is the power factor of the motor.

The apparent input to a three-phase induction motor is

$$\sqrt{3} \cdot E \cdot I \text{ watts.}$$

From the above equations we may easily write the expressions for the efficiency, power factor, and apparent efficiency, as follows:

$$\text{Efficiency} = \frac{0.142\, n'\, T}{\sqrt{3} \cdot E \cdot I \cdot P}$$

$$\text{Power factor} = P = \frac{\sqrt{3} \cdot E \cdot I \cdot P}{\sqrt{3} \cdot E \cdot I}$$

$$\text{Apparent efficiency} = \frac{0.142\, n'\, T}{\sqrt{3} \cdot E \cdot I}$$

Example. A certain 12-pole induction motor whose performance curves are given in Fig. 326, is rated as follows:

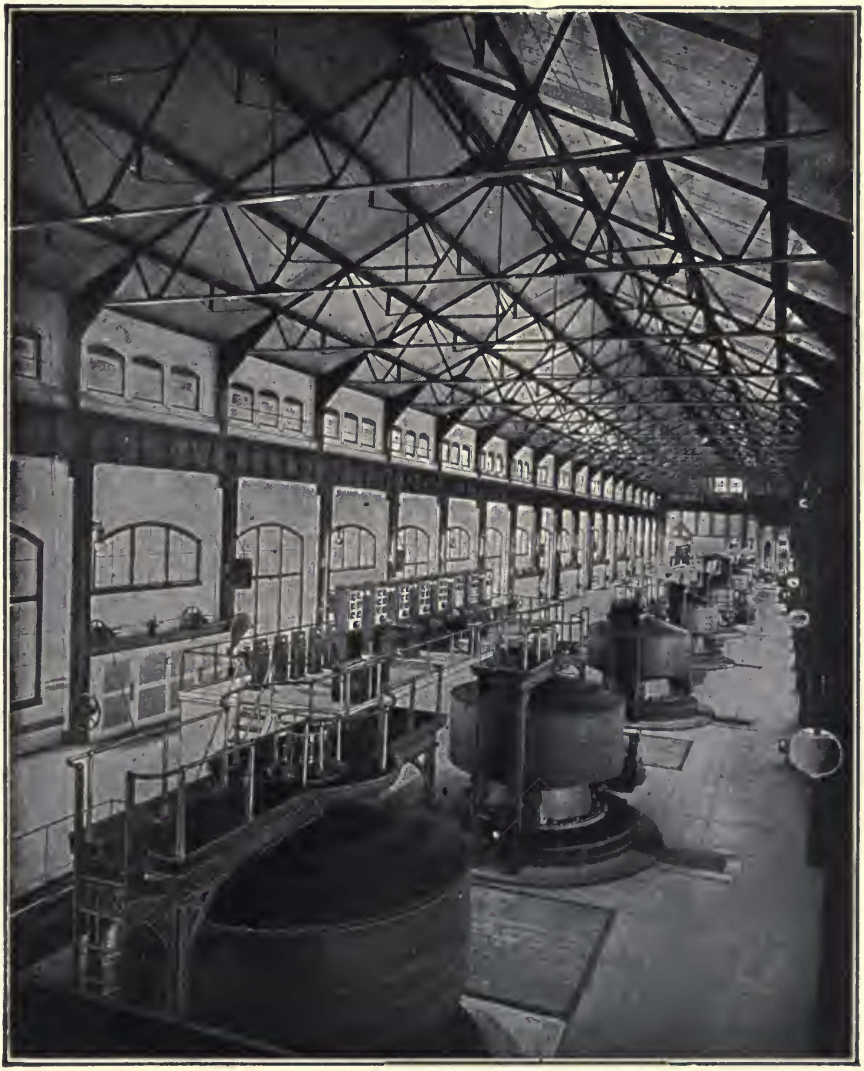
Number of phases, 3;
Output at full load, 175 horse-power;
Voltage supplied (between mains) 550 volts;
Speed, at full load, 585 r.p.m.;
Frequency, cycles per second, 60

A brake test on the motor when running at full load gave the following data (see curves in Fig. 326).

Useful torque on rotor shaft, pound-feet	1,560
Speed, in revolutions per minute, ...	585
Amperes input per phase	170
Power factor, in per cent	88

It is required to calculate the following quantities in order to check the accuracy of the curves plotted in Fig. 326.

(*a*) The synchronous speed in r.p.m.
(*b*) The slip at full load in per cent.



Seven 5000 H. P. Westinghouse Generator at Niagara
Falls Power Co.

(*c*) The useful output in watts and in horse-power.
(*d*) The actual input in watts.
(*e*) The efficiency.
(*f*) The apparent input in watts.
(*g*) The apparent efficiency.

Solution:—

(*a*) The synchronous speed, according to the equation on page 313, is

$$\frac{2f}{p} = \frac{2 \times 60}{12} = 10 \text{ revolutions per second,}$$

or, $10 \times 60 = 600$ r.p.m.

(*b*) The slip according to article 152 is

$$\left(\frac{n - n^1}{n}\right) 100 = \left(\frac{600 - 585}{600}\right) 100 = 2.5 \text{ per cent.}$$

(*c*) The useful output from the above equations is

$$0.142\ n'\ \text{T watts.}$$

Substituting the given values of n' and T,

we have $0.142 \times 585 \times 1560 = 129{,}600$ watts,

which gives $\dfrac{129{,}600}{746} = 173$ horse-power.

(*d*) The actual input in watts is

$$\sqrt{3} \cdot \text{E} \cdot \text{I} \cdot \text{P}$$

whence substituting the given values of E, I, and P

gives $1.732 \times 550 \times 170 \times 0.88 = 142{,}500$ watts.

(*e*) The efficiency (real) is

$$\frac{\text{Useful output}}{\text{Actual input}} = \frac{129{,}600}{142{,}500} = 90.9 \text{ per cent.}$$

(*f*) The apparent input in watts is

$$\sqrt{3} \cdot \text{E} \cdot \text{I}$$

or $1.732 \times 550 \times 170 = 162{,}000$ watts.

(*g*) The apparent efficiency is

$$\frac{\text{Useful output}}{\text{Apparent input}} = \frac{129{,}600}{162{,}000} = 80 \text{ per cent.}$$

A comparison of the above results with the corresponding values obtained from the curves in Fig. 326, shows on the whole a very satisfactory agreement.

The power factors of standard commercial induction motors of American manufacture vary at full load from 0.75 to 0.92, depending upon the size and frequency of the motor. The efficiencies range from 0.80 to 0.92. The apparent efficiencies in motors above 5 H.P. output will be found, as a rule, not less than 0.75. This means that the transformers supplying current to induction motors of average sizes, must have an aggregate capacity of about one kilowatt for every horse-power output of the motors.

The following table gives approximate capacities of standard transformers that should be used with two-phase and three-phase induction motors:

TABLE VIII.

H.P. Capacity Motor.	Three-Phase.		Two-Phase. 2 Transformers.
	2 Transformers.	3 Transformers.	
1	.6 K.W.	.5 K.W.	.6 K.W.
2	1.5 "	1.0 "	1.0 "
3	2.0 "	1.5 "	1.5 "
5	3.0 "	2.0 "	3.0 "
7½	4.0 "	2.5 "	4.0 "
10	5.0 "	3.5 "	5.0 "
15	7.5 "	5.0 "	7.5 "
20	10.0 "	7.5 "	10.0 "
30	15.0 "	10.0 "	15.0 "
50	25.0 "	15.0 "	25.0 "
75		25.0 "	35.0 "
100		30.0 "	45.0 "

SWITCHBOARD AND STATION APPLIANCES.

154. **The Switchboard** is a supporting frame upon which are mounted most of the measuring instruments, safety and controlling devices used in a generating or receiving station.

Lightning arresters are usually mounted on the wall of the station building at the points where the lines enter the building.

Large apparatus such as rheostats, oil-switches, circuit-breakers, and voltage regulators are frequently installed at a distance from the switchboard, and are controlled from the switchboard by systems of levers, by compressed air, or by electrical relays which are in turn controlled by contact switches on the switchboard. Thus Fig. 327 shows a large rheostat mounted underneath the floor upon which the switchboard stands. The rheostat is operated by means of sprocket-wheels and chain which are moved by a hand-wheel on the switchboard.

Alternating-current switchboards differ from direct-current switchboards as follows:

(*a*) On account of the many special devices such as voltage regulators, switchboard transformers, power-factor indicators, and synchronizing devices, which are used in alternating-current work, and are not used in direct-current work.

(*b*) Because of complications associated with the use of an auxiliary direct-current generator for exciting the field magnets of alternators.

(*c*) Because of the frequent use of excessively high voltages, as high as 40,000 volts or more, in alternating-current systems.

Switchboards are now usually built up of standard panels uniform in size, the style varying with the service required. Large switchboards for handling many generators or many feeder circuits, are built up by placing a number of these standard panels side by side. This method of building large switchboards has the following advantages:

1. It reduces the necessity of special work to a minimum, and permits the use of standard apparatus, thus reducing cost.

2. It provides for interchangeability of panels, thus making rearrangement of feeder, generator, and exciter panels easy and convenient.

3. The use of standard panels uniformly equipped with standard apparatus makes it easy and cheap to renew damaged parts.

4. It enables extensions to be made easily and systematically.

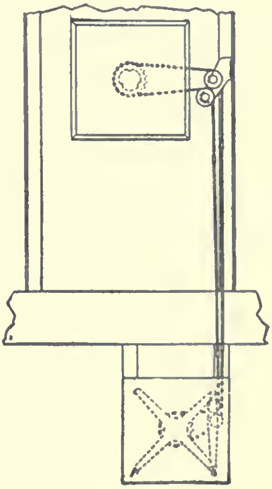


Fig. 327.

In some large stations as many as ten or more generator panels and fifteen or more feeder panels are erected side by side.

The panels of a switchboard are usually erected and wired completely at the factory, and all the instruments are attached.

After thorough inspection and testing, they are shipped to their destination, the instruments being detached, and shipped separately.

Switchboards are usually constructed of a skeleton frame of angle iron, to which panels of marble or slate are fastened by bolts and nuts. The various instruments are attached to the marble or slate panels. In many cases the apparatus itself is located behind the board, the hand-wheel or operating lever, only, being placed on the front of the board.

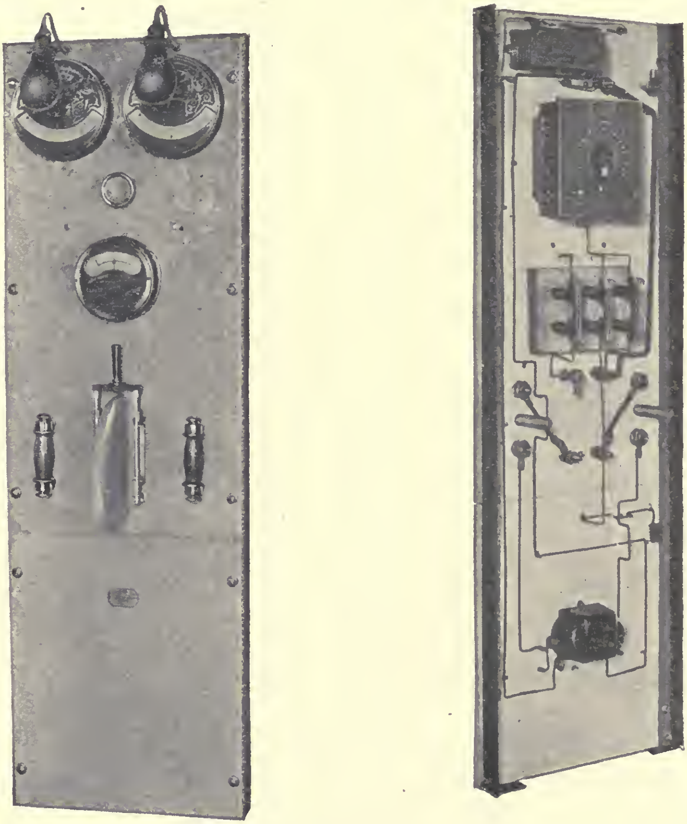


Fig. 328.

Slate, when entirely free from metallic veins, is a fair insulator, but the frequent occurrence of such veins, and the tendency of slate to absorb moisture from the air, render it unreliable, especially for switchboards on which high-voltage apparatus is to be installed. Marble is the standard material for switchboard panels, and it alone is used for high-voltage panels.

155. Typical Single-Phase Switchboard. Fig. 328 shows front and back views of a standard switchboard for one single-phase generator and one feeder circuit. The front elevation of this board and the complete diagram of electrical connections are shown in Fig. 329. Fig. 330 shows the front elevation of a switchboard for one single-phase generator and two feeder circuits, and also the complete diagram of electrical connections. These switchboards are manufactured by the Fort Wayne Electric Works.

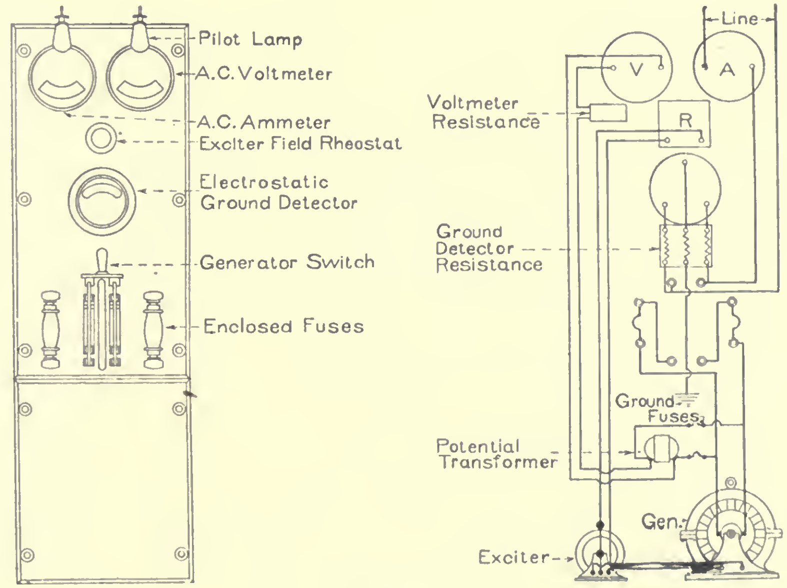


Fig. 329.

The ammeter and voltmeter used on these boards, indeed nearly all switchboard ammeters and voltmeters, are of the "plunger type," that is, they consist of a coil of wire actuating a movable piece of soft iron to which the pointer is attached.

The pilot lamps are for illuminating the board and for indicating that the generator is in operation.

The essential features of the electrostatic ground detector are described in article 31.

The double-pole quick-break generator switch with marble barrier is shown in Fig. 331. It is used for opening and closing the main circuit of the generator as may be seen in the diagram of connections shown in Fig 329. When this switch is opened, the arc which is produced is prevented by the marble barrier from flashing across from blade to blade of the switch, and thus short-circuiting the generator.

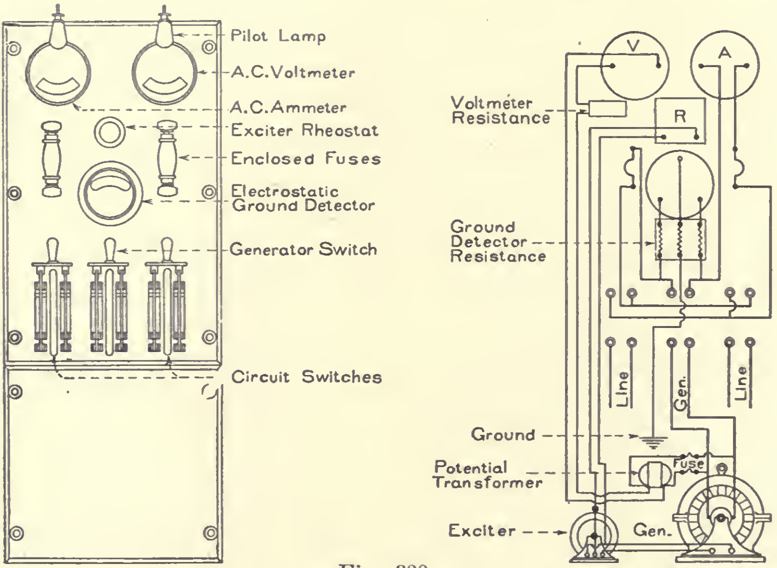


Fig. 330.

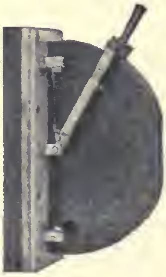


Fig. 331.

The expulsion fuses are ordinary flat fuse links (commonly made of aluminum) surrounded by fire-proof insulating tubes of porcelain. The Westinghouse Company sometimes mount their fuses in a lignum vitæ fuse block enclosed in an air-tight chamber. When the fuse melts and breaks, the arc is extinguished by the explosive action which accompanies the sudden heating of the air enclosed in the fuse chambers. The potential transformer* has its secondary connected through a high resistance to the voltmeter. If the ratio of transformation of the potential transformer is 20 to 1, and the voltmeter reads 110 volts, the voltage between the generator terminals is 20 × 110 = 2,200 volts.

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*The use of the potential transformer in connection with switchboards is explained elsewhere.

156. Typical Switchboard for Operating Two or More Single-Phase Alternators in Parallel. Fig. 332 shows front and side elevations of one of the General Electric Company's standard panels for one of several single-phase generators to be operated in parallel, and a complete diagram of electrical connections. The equipment of this panel is as follows:

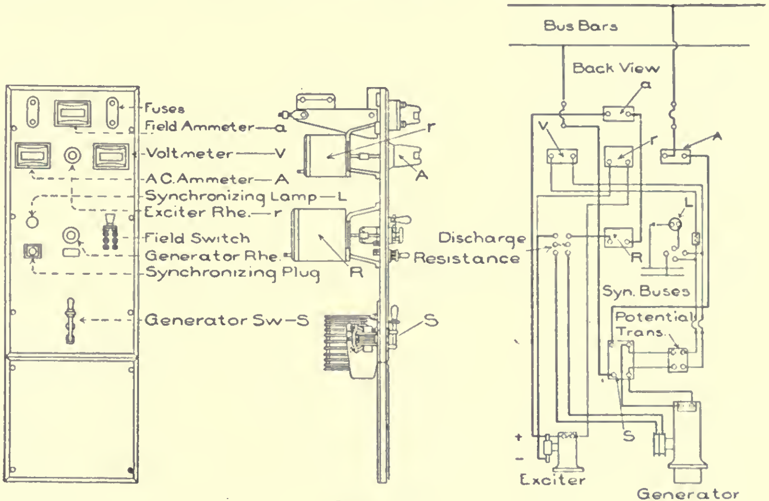

Fig. 332.

1 double-pole generator switch, mounted on the back of the board, and operated by a lever on the front of the board.

2 expulsion fuse blocks complete.

1 generator ammeter.

1 field ammeter.

1 voltmeter and one potential transformer.

1 field switch.

1 sychronizing device, complete.

Tripod and front plate for "generator rheostat" (in the field circuit of the generator) with shaft and hand-wheel.

Tripod and front plate for "exciter rheostat" (in the field circuit of the exciter.)

All necessary framework and connections.

The location of apparatus for this panel, as designated by letter, is as follows:

R = rheostat in the field circuit of the generator, "generator rheostat."
a = ammeter in the field circuit of the generator "field ammeter."

V = voltmeter between the generator terminals (through potential transformer).
A = ammeter for the main alternating current.
L = synchronizing lamp.
S = "generator switch" in the main circuit.
r = rheostat in the exciter field circuit, "exciter rheostat."

This apparatus is essentially the same as the apparatus already described in article 155 with the exception of the ground detector, the field switch with discharge resistance, and the synchronizing device. One ground detector is sufficient for a number of machines operated in parallel, and it is usually mounted on a bracket attached to one of the generator panels. The field switch is arranged to short-circuit the field winding of the alternator at (or just before) the instant of disconnecting the exciter from the field windings. This allows the current in the field winding to die away slowly. The opening of a field switch which is not provided with a resistance produces an excessively high electromotive force between the field terminals, which is likely to cause puncture of the insulation of the field windings.

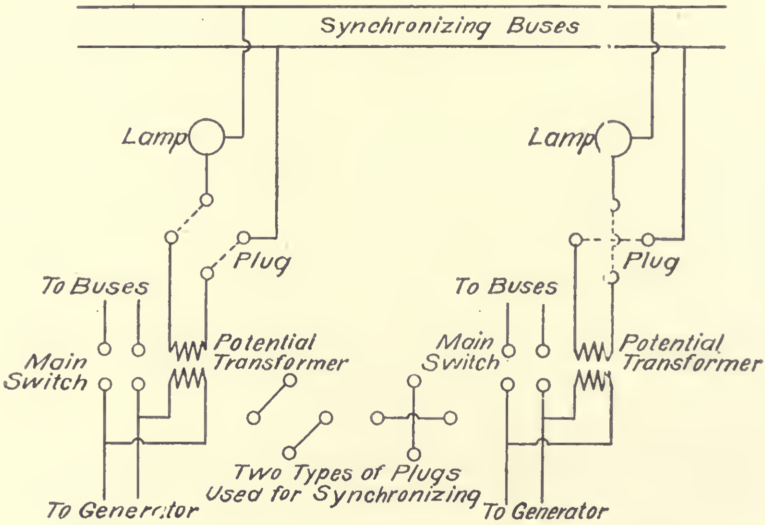

Fig. 333.

The synchronizing device consists of the synchronizing busbars connecting the various generator panels, the synchronizing lamps, a small transformer (the same one being used for the voltmeter) for stepping down the voltage to a suitable value for the synchronizing lamps, and connection plugs for connecting the secondary of the potential transformer through the synchronizing lamps to the synchronizing busses. Two types of connecting plugs are used, one of which reverses the connections made by the other. The complete connections of the synchronizing device for two single-phase machines is shown in Fig. 333.

In case of polyphase machines, one phase only is connected to the synchronizing device, and the synchronizing device is therefore the same for single-phase and for polyphase alternators. The operation of alternators in parallel is very common in modern central stations.

The voltmeters and synchronizing device are always connected back of the main generator switch, that is, between the generator and the switch, for the reason that the voltage of the machine must be synchronized *before* the main switch is closed.

The connections of the two types of synchronizer plugs are shown in Fig. 333. Neither plug is used when one alternator only is operated. When another machine is to be put into operation, either type of plug is used to connect the synchronizer busses to any one of the machines already running, and the other type of plug is used for connecting the machine which is being synchronized, to the synchronizing busses. Thus the synchronizer busses are *oppositely* connected to the two machines, and the synchronizing lamps are *bright* when the conditions are proper for closing the main switch. This is the common practice of the General Electric Company.

When alternators having composite field* windings are operated in parallel, a slight increase of current output from one machine would, in passing through the rectifying commutator and the series field winding, cause the current output to still further increase. That is, composite alternators will not operate stably in parallel unless provision is made to cause the current in the series field windings of all the machines to increase and decrease simultaneously. This is accomplished by feeding all the series field windings in parallel between bus-bars to which all the rectifying commutators supply uni-directional current. These bus-bars, called the equalizer busses, must, of course, be connected to all of the generator switch-board panels.

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*See article 43.

When more than two generators are operated in parallel, and one direct-current generator is used as an exciter for supplying current to the field windings of all the alternators, a separate switchboard panel called the exciter panel, is usually installed. Upon this panel the exciter field rheostat and controlling devices are mounted. In this case exciter bus-bars are led from the exciter panel to all the main generator panels.

157. Conditions Necessary for Parallel Operation of Alternators. In the parallel or multiple operation of alternators, there are three elements which need special consideration—frequency, phase, and voltage. It is necessary that the generators be similar in these respects, to insure their working together properly when connected in parallel.*

(*a*) Frequency. Two generators are of the same frequency when the numbers of alternations or reversals of their electromotive forces in a given time are equal. This requirement is fulfilled when the product of the number of poles by the revolutions per minute is the same for each machine.

The frequency of a generator, being dependent upon its speed, may be controlled by the regulation of the speed of its prime mover.

(*b*) Phase. Two generators are in phase when the positions of their armatures with respect to their field poles are the same. *i.e.*, when similar armature coils are opposite positive field poles at the same instants. When this condition exists the electromotive forces of the machines are both positive at the same time, and their maximum values occur at the same instant; the electromotive forces are said to be coincident in phase.

(*c*) Voltage. Two generators are of the same voltage when the pressure measured across the armature terminals is the same for each machine.

The voltage for a given speed being dependent upon the field strength may be controlled by means of the rheostat in the field circuit.

158. Determination of Relative Frequency and Phase Coincidence. If two similar generators are running at exactly the same speed their difference in phase remains constant. This condition, however, does not exist in practice unless the armatures are rigidly connected, as the inevitable fluctuation in engine and water-wheel speeds and in belt slippage causes the position of the armatures with reference to their field poles to be continually changing, and consequently the difference between the phases to be likewise changing. As generators should not be thrown in parallel excepting when their frequencies are practically the same, and at the time their phases are in exact coincidence, or nearly so, it is essential to have an accurate means of determining when these conditions exist.

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*Furthermore, two alternators, to operate satisfactorily in parallel must have electromotive force waves of the same shape.

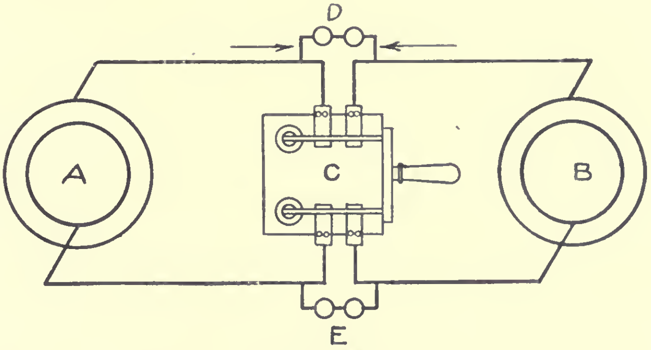

Fig. 334.

The principle of the most common method of determining when generators are of the same frequency and are coincident in phase, is illustrated in Fig. 334. A and B represent two single-phase generators, the leads of which are connected at the switch C, through two series of incandescent lamps D and E. It is evident that as the relative positions of the phases of the electromotive forces change from that of exact coincidence to that of exact opposition, the flow of current through the lamps varies from a minimum when the machines oppose each other in forcing current through the lamps as shown by the arrows in Fig. 334, to a maximum when the machines help each other in forcing current through the lamps.* If the electromotive forces of the two machines are exactly equal and in phase, the current through the lamps will be zero, and as the difference in phase increases, the lamps will light up and will increase in brilliancy until the maximum is reached; when the phases are in exact opposition. From this condition they will decrease in brilliancy until completely dark, indicating that the machines are again in phase. The rate of pulsations of the lamps depends upon the difference in frequency, *i. e.*, upon the difference in the speeds of the machines, and by adjustment of the governors of the engine or water-wheel, or the tension of the belt, the rate can generally be reduced to as low as one pulsation in ten seconds, which affords ample time for throwing the switch connecting the generators in parallel.

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* When the two machines oppose each other in forcing current through the lamps they would help each other, or be in phase with each other, in producing current in the receiving circuit to which the machines are to be connected in parallel.

The Synchronizer. When the phases of two generators coincide, the machines are said to be "in phase", "in step", or "in synchronism". The apparatus used for determining when generators are in phase is called a "synchronizer". In Fig. 334 the lamps constitute the synchronizer. While a series of lamps, alone, may be used for synchronizing machines of very low voltage, it is not safe or practical to use this method for machines of high voltage. The most common arrangement for synchronizing alternators, in general, is illustrated in the diagram, Fig. 335. A and B represent the two single-phase generators with switches in the main leads. There are two transformers, the primaries of which are connected across the main leads of A and B respectively, the secondaries being connected in series through the lamps E. Now, if the transformers are connected similarly in the two circuits, as shown in the diagram, then when the generators A and B are in phase the electromotive forces in

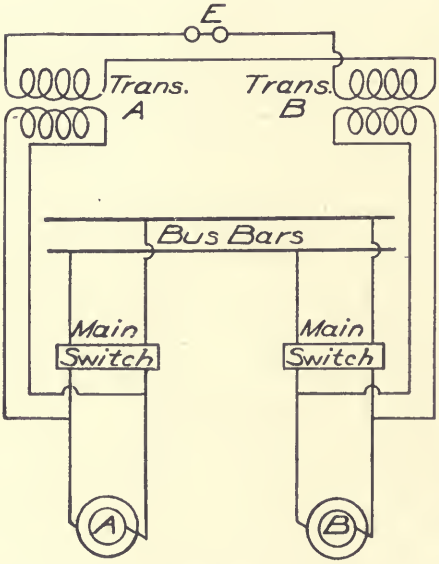


Fig. 335.

the secondaries will be in phase and no current will flow through the lamps, and when the generators are out of phase, the electromotive forces in the secondary circuits will be out of phase also, and current will flow through the lamps. The amount of this current and the resultant brilliancy of the lamps depends on the difference in phase. If the connections of either the primary or secondary of either transformer be now reversed from those shown in Fig. 335, the indications of the lamps will be reversed; that is, when the generators are in phase the lamps will burn at maximum brilliancy, and *vice versa*. It is the *common practice of the Westinghouse Company to arrange the transformer connections so that the lamps shall be dark when the generators are in phase.*

In order to determine whether the synchronizer lamps will be bright or dark for a given connection of transformers when the generators are coincident in phase, remove the main fuses or raise collector brushes from one machine, and throw in the main switches with the other generator at full voltage. Since both primaries are now connected through the switches to one machine, the lamps will be in the same condition as when the main or paralleling switches are open and both generators are coincident in phase. If the lamps burn brightly and it is desired that they be dark for an indication of phase coincidence, the connections of one of the primaries or of one of the secondaries of the transformers should be reversed.

The lamps which are used with the synchronizer should be adapted for the highest voltage which they will receive. Thus, if they are placed upon the secondaries of two 100-volt transformers, there should be two 100-lamps or four 50-volt lamps in series. If two 200-volt machines have the lamps applied directly without transformers it will be necessary to use four 100-volt lamps, or their equivalent.

Rate of Pulsation and Size of Pulley. The difference in speed between two machines may be determined by the rate of pulsation of the synchronizing lamps. It is sometimes convenient to know this difference in speed, especially when two generators are belt-driven from the same shaft. If the speeds are not equal, it may be necessary to turn off one of the pulleys in order to make them equal. One pulsation of the lamps, *i.e.*, the interval between two consecutive occurrences of maximum brilliancy, indicates a gain of one cycle or two alternations of one machine over the other. Thus, if there is one pulsation of brightness per minute, and the number of alternations is 7,200 per minute, then one machine gives 7,202 alternations, while the other gives 7,200. If the number of pulsations of brightness is 36 per minute, then one machine gives 7,272 alternations, while the other gives 7,200 alternations, and the first machine is therefore running 1 per cent. faster than the second machine. In order to determine which machine is running the faster, the load may be thrown upon one machine, or its belt may be slackened so as to decrease its speed. If this be done to the machine which attempts to run too fast, the pulsations will become less rapid; while if it be done to the machine which is running slower, the pulsations will become more rapid. If one machine is running 1 per cent faster than the other, it will be necessary to reduce the diameter of the pulley of the other (slower) machine by 1 per cent.

The thickness of the belt, the tightness of the belt, the slippage (dependent upon the kind of belt, the condition of the surfaces of the pulley and belt, and the load) are all factors which affect the speed and must all be kept in mind.

159. Directions for Connecting One Alternator in Parallel with Another Alternator.

1. *Frequency.* The speed of the new machine which is to be connected in parallel must be made such as to give the same frequency as the one already running. If the latter is carrying a load, it may be necessary to reduce the speed of the unloaded machine below that at which it tends to run with no load, by adjusting the engine valve, or the water wheel gate or nozzle, or the belt slippage, in order to secure the proper speed.

The adjustment of the engine should preferably not be by throttling, as the governor is liable to "hunt" when the throttle is opened. It is desirable to be able to adjust the governor for changing the speed while the engine is running.

2. *Voltage.* The field excitation of the new machine should be adjusted so that its voltage is the same as that on the bus bars, the measurement being made by a voltmeter.

3. *Phase Coincidence.* Synchronizer lamps indicate by their slow rate of pulsation that the machines are of practically

equal frequency. When the synchronizer lamps indicate the proper phase relation, *i.e.*, phase coincidence (preferably when the lamps are dark), all is ready for closing the switch.

4. Close the main switch. It is better to close the switch a little too soon (when the machines are approaching the proper position) than too late (when they are receding from it). If the switch is operated by compressed air or for any other reason does not close the instant the handle is operated, due allowance must be made for the interval.

5. If the generators are composite wound, close the equalizer switch.

6. Adjustment may now be made by means of the governor or otherwise so that each machine receives its proper share of load.

7. The field currents of the several generators should be properly adjusted to eliminate cross currents between the armatures and maintain the proper voltage on the bus-bars.

160. Directions for Cutting Out An Alternator Which is Running in Parallel With One or More Alternators. 1. Preferably cut down the driving power until it is just about sufficient to run the generator at zero load. This will automatically reduce the load on the generator.

2. Adjust the resistance in the field winding of the machine which is to be cut out until its armature current is a minimum.

3. Open the main switch, then the equalizer switch.

It is usually sufficient, however, to simply disconnect a machine from the bus-bars, thereby throwing all the load suddenly on the remaining machines, without having made any special adjustments of the load or the field current. The objection to this method is that it may cause serious hunting of the remaining machines.

NOTE. The field circuit of the generator to be disconnected from the bus-bars must not be opened before the main switch has been opened; for if the field were opened first a heavy current would flow between the armatures.

161. Typical Switchboard Panel for Two-Phase Alternator Operated in Parallel With Other Two-Phase Machines. Fig. 336 shows front and side elevations, and complete wiring diagram (back view), of one of the General Electric Company's switchboard panels for a two-phase alternator which is to be operated in parallel with other two-phase machines.

The potential transformer which supplies reduced voltage to the voltmeter and to the synchronizing buses has its primary connected across *one phase* of the generator, and the synchronizing device is exactly the same as for the single-phase machines.

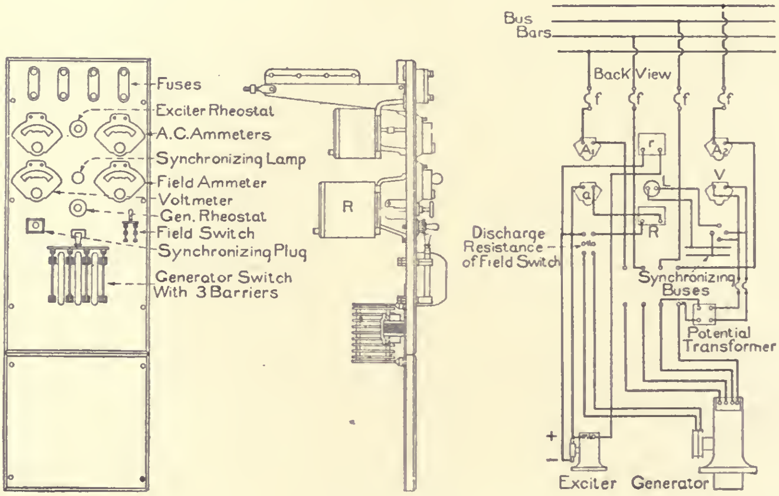


Fig. 336.

The equipment of this two-phase generator panel differs from that of the single-phase panel shown in Fig. 332, in the following particulars:

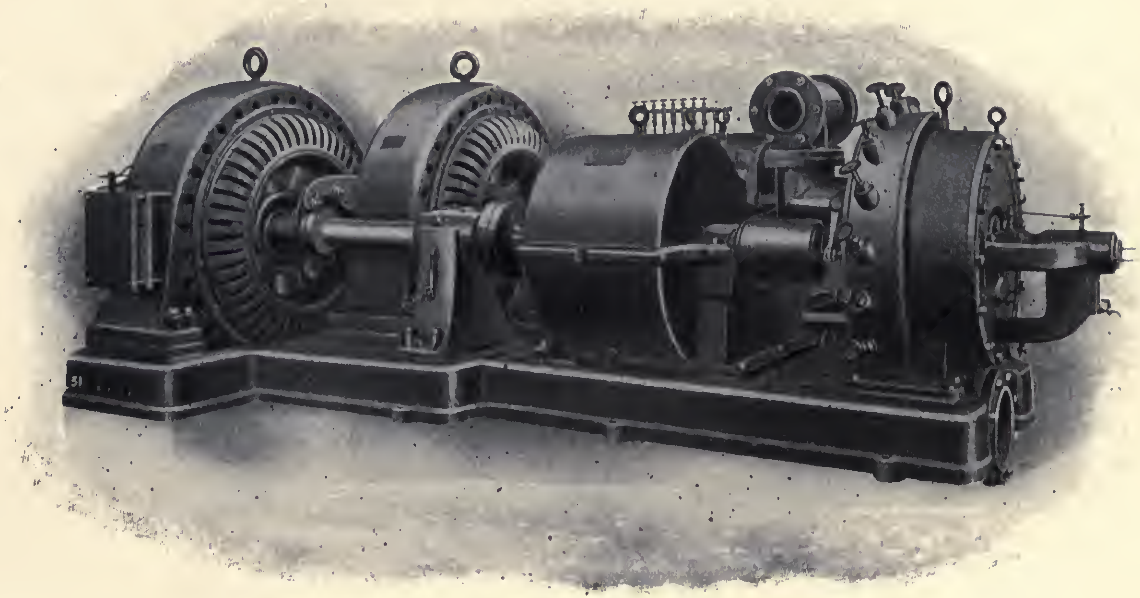
(*a*) The main generator switch is a four-pole switch for connecting the four leads from the generator to the four lines which pass out from the top of the board through four fuses.

(*b*) Two alternating current ammeters are used, one for each phase.

The "generator rheostat" is in the field circuit of the two-phase generator, and the "exciter rheostat" is in the field circuit of the exciter, exactly as in Fig. 332.

The equipment of apparatus for this panel is as follows :

R = rheostat in the field circuit of the generator, "generator rheostat".
a = ammeter in the field circuit of the generator, "field ammeter".
V = voltmeter between the terminals of one phase of the generator (through the potential transformer).



TURBINE ALTERNATOR. 200 K.W. 300 H.P.

De Laval Steam Turbine Co.

A_1 and A_2 = ammeters, one for each phase of the generator.
L = synchronizing lamp.
r = rheostat in the field circuit of the exciter, "exciter rheostat".
f, f, f, f = fuses.

The four small circles above and below the words "synchronizing busses" are the points of the four-pole main switch.

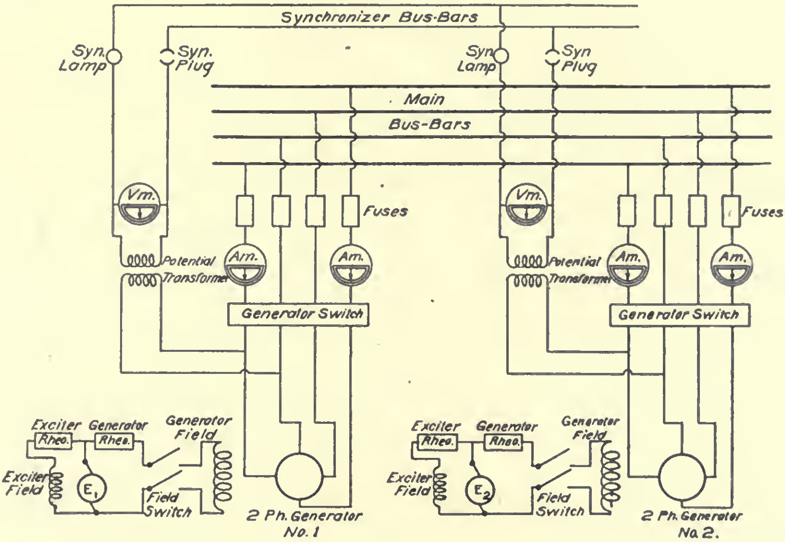


Fig. 337.

Fig. 337 shows the complete connections of two two-phase generators for parallel running.

162. Typical Switchboard Panel for Three-Phase Generator Operated in Parallel with Other Three-Phase Machines. Fig. 338 shows front and side elevations, and complete wiring diagram (back view) of one of the General Electric Company's switchboard panels for a three-phase alternator, which is to be operated in parallel with other three-phase machines. The potential transformer which supplies reduced voltage to the voltmeter and to the synchronizing busses has its primary connected across one phase of the generator, and the synchronizing device is exactly the same as for single-phase machines.

The equipment of this three-phase panel differs from that of the single-phase and two-phase panels shown in Figs. 332 and 336, in the following particulars :

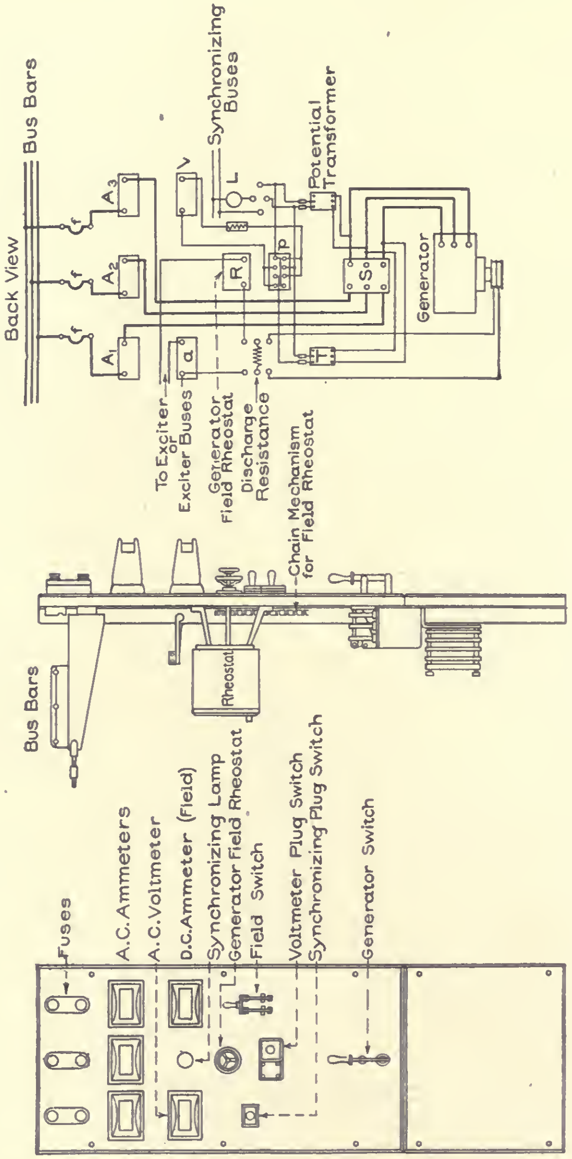


Fig. 338.

(*a*) The main generator switch is a three-pole switch for connecting the three generator leads to the three lines which pass out from the top of the board through three fuses.

(*b*) Three alternating-current ammeters are used, one for each phase.

Fig. 338 also shows the following points, which however, are not characteristic of a three-phase panel, but might be used on a two-phase panel.

(*a*) The two phases not connected to the potential transformer proper, are stepped-down to a reduced voltage by the use of one additional potential transformer T, Fig. 338.

As explained in article 133, two transformers suffice for stepping-down three phases to two phases. Both potential transformers have their secondaries connected to a "voltmeter plug switch", by means of which the voltmeter may be connected so as to indicate, at the will of the operator, the voltage of any one of the three phases.

(*b*) The lines which pass out at the top of the panel in Fig. 338 are shown connected to the three main bus-bars or rods.

(*c*) No exciter is shown in Fig. 338, and no exciter field rheostat, but the panel is arranged so that one large exciter may be used for all the generators. For this purpose exciter busses (two of them), connect the one large exciter to all the generator panels.

(*d*) The generator field rheostat is geared to the hand wheel by means of sprocket wheels and chain on the back of the switchboard.

The equipment of apparatus for this panel is as follows :

R = "generator field rheostat".
a = ammeter (direct-current) in the field of the generator.
V = voltmeter between the terminals of one phase of the generator (through potential transformer).
p = voltmeter plug switch.
A_1, A_2, A_3 = ammeters for alternating currents, one in each phase of the generator.
L = synchronizing lamp.
S = main generator switch,
f, *f*, *f* = fuses.
T = additional potential transformer.

163. Feeder Panels. In large generating stations, the bus-bars, to which the various generators are connected in parallel, lead from the generator panels to the feeder panels. The feeders are the separate and distinct circuits which receive current from the bus-bars, and transmit it outside the station to points more or less remote. Each pair of feeders (or set of three or four in polyphase distribution), as it comes into the station, is protected by lightning arresters as explained elsewhere. From the lightning arresters the feeders are brought to the feeder panels through fuse blocks, and through ammeters, and connected to bus-bars by means of suitable switches.

When there are but few feeder circuits, the feeder switches are mounted on the generator panel as shown in Fig. 330.

Ground detectors are used primarily for detecting grounds on feeder circuits, and where many feeders are connected to the bus-bars, the ground detectors are mounted on the feeder panels. When there are but few feeder circuits the ground detector may be connected to the bus-bars, in which case the ground detector may be mounted on a generator panel or on a feeder panel, if feeder panels are used.

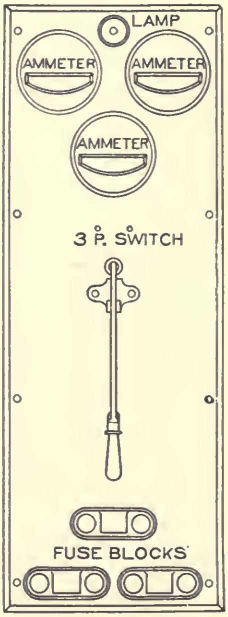


Fig. 339.

It is frequently desirable to control the voltage supplied to a feeder circuit independently of the voltage between the bus-bars. For this purpose voltage or potential regulators are used, and these voltage regulators are either mounted upon the feeder panels or are controlled by levers or hand wheels which are mounted on the feeder panels.

When the energy (watt-hours) delivered to a feeder circuit is to be measured, the recording wattmeter is mounted on the feeder panel.

Circuit breakers, when used, are usually mounted upon the feeder panels and arranged to open the feeder switch when the current delivered to the feeder becomes excessive.

Fig. 339 shows a front elevation of a typical three-phase feeder panel manufactured by the Westinghouse Electric and Mfg. Company. The equipment of this panel includes the following apparatus:

1 pilot lamp, bracket, and shade.

3 alternating-current ammeters, one for each line of the three-line feeder.

1 three-pole high-voltage double-break plunger switch, mounted back of the panel and operated by a lever on the front of the panel.

3 single-pole fuse blocks.

164. High-Voltage Switchboard Panels. In alternating-current generating stations for long distance transmission, the alternating currents are generated at a medium or low voltage, and are then stepped-up to 10,000 to 40,000 volts or more for transmission. In such stations, the low voltage switches and controlling devices, including exciter switches and rheostats, are mounted on panels separate from the high-voltage switches and devices. Such stations have, therefore, low-voltage panels and high-voltage panels. The high-voltage panels differ from the low-voltage panels in having very much greater distances between the high-voltage parts, in order to avoid the danger of short-circuit by sparking across through the air, and in having special forms of switches. These special switches are described in following articles with other forms of switchboard apparatus.

Special Switchboard Panels. Usually the fuses, switches, starting and controlling devices which are used in connection with a synchronous or induction motor, a rotary converter, or a motor-generator, are for convenience mounted upon a switchboard panel.

SPECIAL SWITCHBOARD APPARATUS.

165. The Lincoln Synchronizer. When incandescent lamps are used as synchronism indicators in the starting of a synchronous motor, or in the paralleling of alternators, the pulsations of brightness indicate only the *difference* in frequency of the two machines, and it is in general impossible to tell from the behavior of the lamps which of the machines is running at the greater frequency.

The Lincoln synchronizer is a device for indicating positively the difference in the frequency of two alternators which are being adjusted into synchronism, and also for indicating positively the phase difference of the two machines at each instant.

The Lincoln synchronizer is a very small machine of which the iron parts are exactly like the field magnet and armature core of a very small two-pole direct-current motor, except that both field magnet and armature core are laminated. The field magnet is excited with alternating current by connecting the field winding to the terminals of A, of the alternators A and B, which are being synchronized. The armature of the synchronizer is wound with two coils *c* and *d* at right angles to each other. Each of these coils is independently connected through collecting rings to the terminals of alternator B. Coil *c* has connected in series with it a non-inductive resistance, and coil *d* has connected in series with it a large inductance. The armature of the small machine has attached to it a pointer which moves over a divided circle. When machines A and B have exactly the same frequency, this pointer is stationary, and its reading on the circle indicates the phase difference between the two machines. When machine A is running at a slightly greater frequency than B, the pointer rotates in a certain direction indicating at each instant the changing phase-difference between A and B. When machine A is running at a slightly lower frequency than B, the pointer rotates in the opposite direction, indicating at each instant the changing phase-difference between A and B. The speed of the pointer in revolutions per second is in each case equal to the difference in frequency of machines A and B, in cycles per second.

Of course the connection of the synchronizer to the terminals of machines A and B may be either direct or through step-down transformers. Generally the latter method of connection is employed.

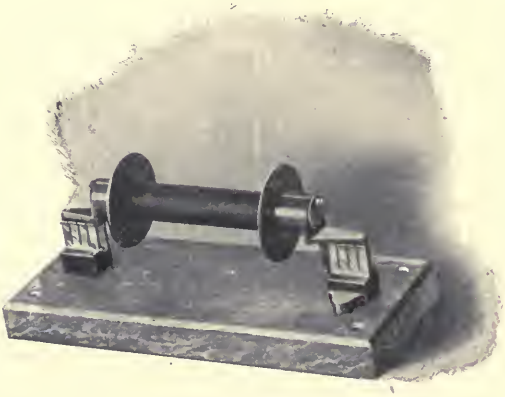


Fig. 340.

166. Fuses. The expulsion type of fuse, much used for medium voltages in alternating-current systems, is described in article 108e, in connection with transformer fuse blocks.

A general view of a Stanley expulsion or "barrel" fuse for medium voltage is shown in Fig. 340. The inclosing tube made of highly insulating and fireproof material has metal caps on its ends, to which are attached the metal blades which fit into the spring clips between which the fuse is to be connected. The inclosing tube, or barrel, serves as a handle by which the device is held while it is being pushed into place. The metal blades are provided with holes which match corresponding holes in the spring clips in which pins are placed to prevent the device from being withdrawn from the clips. The vent out of which the metallic vapors are blown when the fuse melts, is at the end of the barrel. In the Westinghouse expulsion fuses described in article 108e, the vents are located on the sides of the barrel opposite the position of the attendant's hand as he replaces the fuse barrel in position.

A slightly different style of barrel fuse is shown in Fig. 341, in which the handle is distinct from the enclosing tube.

167. Special Switches. Special styles of switches are required in many cases in alternating-current work on account of the excessively high voltages, especially when the switch has to handle large currents at high voltage.

The use of a marble slab between the blades and contact points of a double-pole switch, as a barrier for preventing the arcs, which are formed when the switch is opened, from flashing across and short-circuiting the points of the switch which are connected to the generator terminals, has already been mentioned in article 155. Such a switch with marble barrier is shown in Fig. 331.

Arcing is reduced to a minimum in every case by opening the switch very quickly, and all of the special alternating-current switches described below, are arranged to open with a snap, even though the controlling lever is moved slowly.

Multiple-break switches are used to lessen the trouble from arcing. A *multiple-break* switch is one which makes two or more breaks (in series) in a circuit simultaneously. Some of the special switches described below are double-break switches.

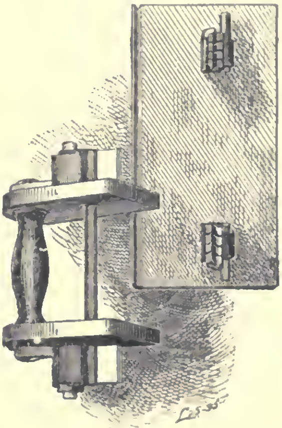


Fig. 341.

Damage to switch-blades and clips, due to arcing, is reduced to a minimum by providing carbon blocks which make a connection in parallel with the switch connection proper. When the switch is opened, the metal connection is broken first, and the carbon connections afterwards, so that the arcing always takes place between the carbon blocks.

The same methods are available for suppressing the arc between the break points of a switch as for suppressing the arc which tends to maintain itself between the terminals of a fuse link when the link fuses. Thus some of the switches to be described break the circuit between the end of a movable copper rod and a stationary copper socket, both of which are surrounded by a porcelain tube, thus utilizing the expulsion principle for suppressing the arc.

The most effective method for suppressing the arc on a high-voltage switch is to design the switch so as to open quickly under oil, and for very high voltages to provide for several simultaneous breaks in series. Oil-switches are now almost universally used in large modern high-voltage stations.

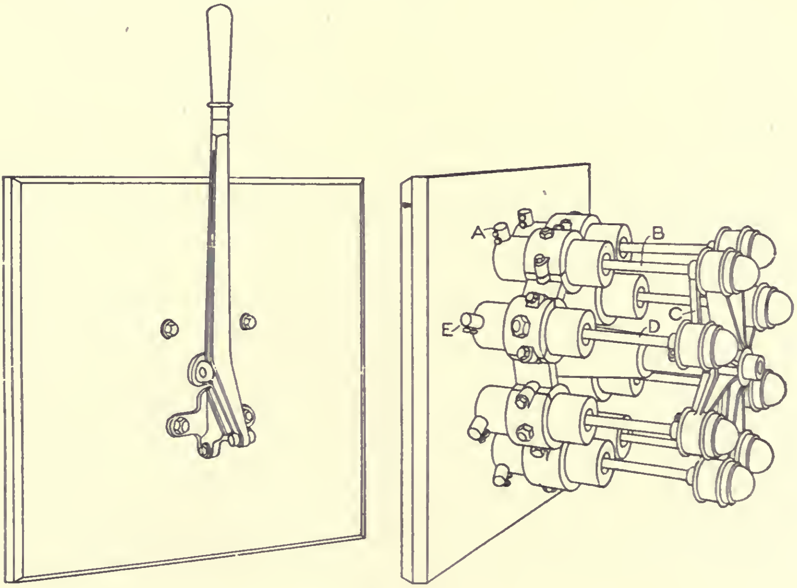


Fig. 342.

Fig. 342 shows a high-voltage four-pole double-break snap switch manufactured by the Westinghouse Electric and Manufacturing Company. It is arranged so that the breaks occur in porcelain tubes in order to suppress the arcs by expulsion, as in the case of expulsion or barrel fuses. This switch is ordinarily mounted on the back of the switchboard, and is operated by a lever on the front of the board as shown.

A cast-iron frame, mounted upon the back of the marble panel, serves as a support for the porcelain cylinders as well as a guide for the operating rod which passes through the long central socket as shown in the figure. This operating rod is controlled by the lever on the front of the panel.

The slender copper rods or plungers, shown in the figure, are fixed to a metal spider or crosshead, being insulated from the spider by thick insulating bushings. This spider is supported on the end of the operating rod, upon which is a collar which compresses a helical spring when the switch is closed by pulling down the operating lever. As the switch is closed the copper rods enter the porcelain cylinders and make contact with spring sockets, which are in metallic connection with the binding posts shown at the base of each porcelain cylinder.

When the switch is opened, the movement of the controlling lever trips a catch which releases the operating rod, and the compressed spring throws the crosshead and attached copper rods outwards, thus suddenly breaking the circuit, or circuits, which are controlled by the switch.

The switch shown in Fig. 342 is designed to connect four wires from a two-phase generator to the four wires leading to the bus-bars, or to a four-wire feeder circuit. This requires eight porcelain cylinders and eight plunger rods to give a double break in each of the four distinct circuits. The four leads from the two-phase generator are brought to alternate binding posts, shown mounted on the left-hand ends of the porcelain cylinders, whereas the four circuit wires are connected to the four remaining binding posts. The copper plunger rods are connected together in pairs by metal bridges near the supporting spider. One of these bridges shows in Fig. 342.

Any one of the four distinct electrical circuits is completed through the switch, as follows: One of the four dynamo leads is connected to the binding post A, whence the current passes up rod B, across the bridge C, and down the rod D, to a feeder wire connected to the binding post E.

Fig. 343 shows a three-pole double-break spring or snap oil switch manufactured by the General Electric Co. This figure shows the switch with the oil tank removed. This particular

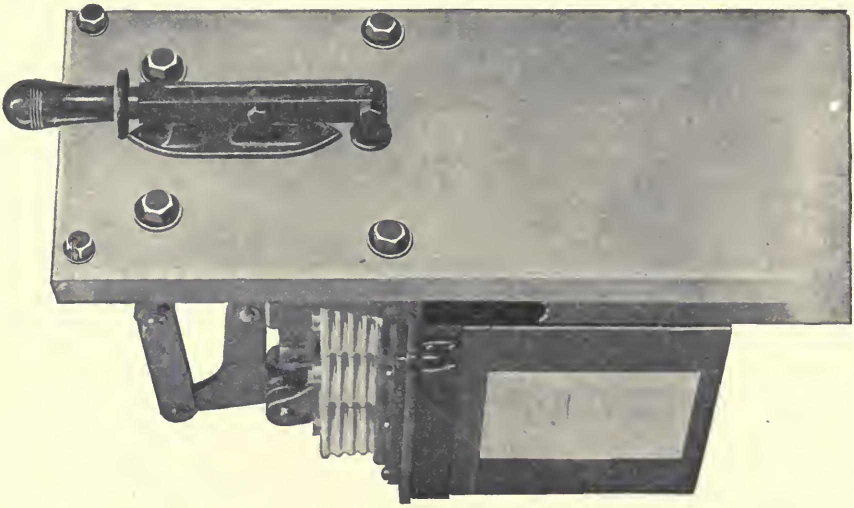


Fig. 344

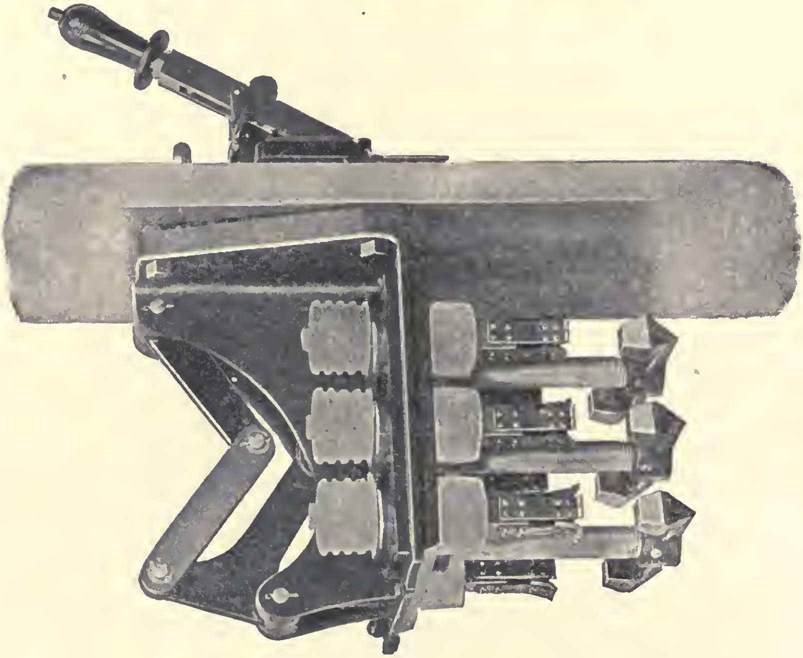


Fig 343.

switch has a trip mechanism which is released electrically, as i the ordinary direct-current circuit breaker, by an iron plunger which is moved by a solenoid through which flows the alternating current (one of the three currents controlled by the switch). When the trip mechanism is released, the switch opens with a snap, and it is closed by hand.

Fig. 344 shows the same type of switch as is shown in 343 but with the oil tank in position. This particular switch is operated by hand.

The six leads for the three-pole switch shown in Fig. 343. pass through long porcelain bushings in the metal bracket which serves as the support for the switch mechanism, and as a cover for the oil tank. These leads connect to the spring sockets shown in the figure. The three vertical rods shown in the figure are made of well-seasoned wood, and each of these wooden rods carries at its lower end a metal cross-piece with two conical lugs. When the switch is closed, these cross-pieces are drawn up and the conical lugs are forced into the spring sockets, thus making connections across between each pair of spring sockets. When the switch is opened, the wooden rods are pushed suddenly downwards making two breaks in each circuit.

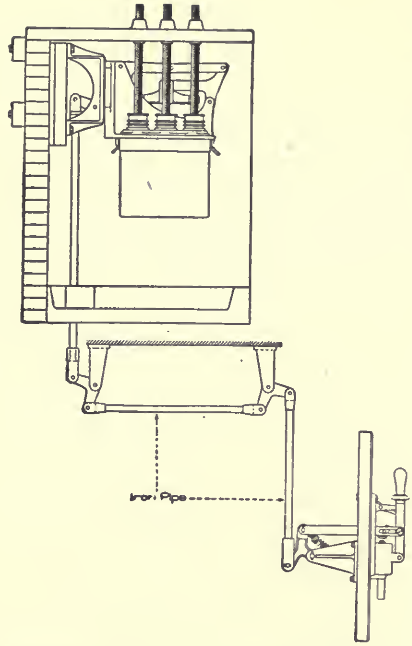
The oil switches of the General Electric Company are manufactured single-pole, double-pole, triple-pole, and four-pole, all being of the single-throw type, and in three general forms, as follows:

(*a*) Hand-operated (Fig. 344) for mounting directly upon the switchboard.

(*b*) For installation at a remote point within fireproof compartments, or "cells" made of brick, and for hand operation from the front of the switchboard through a system of levers. The arrangement of levers is shown in Figs. 345, 346, 347, and 348. For systems in which the voltage exceeds 5,000, the switches are usually remote from the switchboard. It is especially desirable to enclose oil switches in fireproof compartments, inasmuch as the explosive action of the arc under oil sometimes throws the oil out of the tank and may set fire to it at the same time.

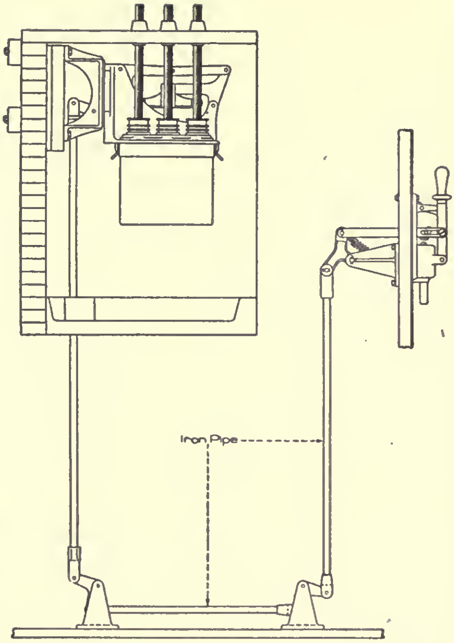
(*c*) For use in combination with an electrically-operated tripping mechanism, making the switch into an automatic circuit breaker. This form is made for mounting upon the switchboard as shown in Fig. 343, or for remote installation, as desired.

Fig. 349 is a general view of a General Electric three-pole oil switch, or rather three single-pole switches operated by an electric



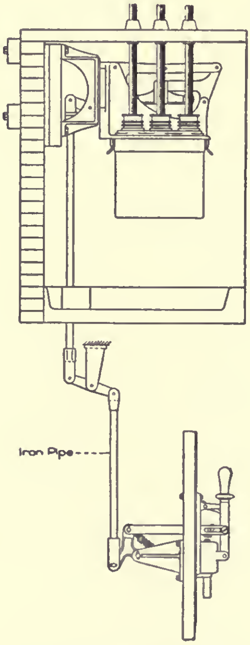
Arrangement of Oil Switches Located Above and Back of Operating Panel.

Fig. 345.



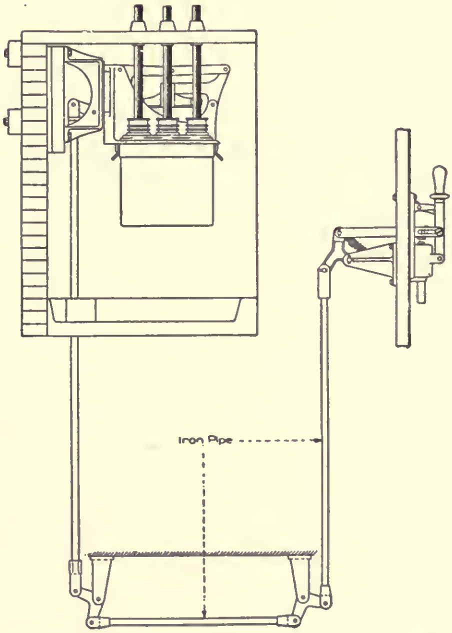
Arrangement of Oil Switches Located Below and Back of Operating Panel.

Fig. 347.



Arrangement of Oil Switches Located Above Operating Panel.

Fig. 346.



Arrangement of Oil Switches Located Back of Operating Panel.

Fig. 348.

motor, which is controlled from the switchboard. Each single-pole switch in Fig. 349 is mounted in a separate brick compartment. The oil is contained in long metal cylinders in order to reduce the amount of oil to a minimum. The long brass connecting rods pass through holes in the porcelain bushings in the tops of the cylinders, and the ends of these rods carry conical lugs which fit into spring sockets. These spring sockets are connected to rods which pass out through porcelain bushings in the bottoms of the cylinders, and these lower rods are connected together in each compartment, thus making a double break single-pole switch. The metal cylinders in Fig. 349, and the metal tanks in Figs. 343 and 344 are entirely insulated from the switch points proper.

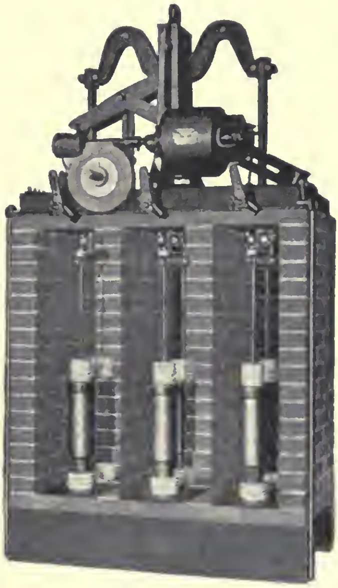


Fig. 349.

The type of oil switch illustrated in Fig. 349 is today the standard for high voltage circuits carrying large alternating currents, and is used extensively in many of the most recent high-voltage generating stations.

Fig. 350 shows a common form of knife switch specially constructed to give a quick break. The switch blade is in two parts *a* and *b*, to one of which (*a*) is attached the operating handle. The two parts *a* and *b* of the blade are connected by strong helical springs *s s*, one on each side of the blade. When the handle is pulled forward to open the switch, blade *a* leaves clip *c*, while the springs are put in tension more and more until the switch blade *b* is pulled from the clip *c*, with a snap, thus causing a sudden breaking of the circuit. Fig. 350 shows two single-pole quick-break switches. The one on the left, designed for 600 amperes, is provided with two massive tubular terminals *t t*, into which the terminals of the main circuit are inserted and soldered. The switch on the right, designed to carry 3,600 amperes, is furnished with massive studs *d d*, which project through holes drilled in the switchboard to the back of the board. Connection to these studs is made by clamping the terminals of the main circuit to them by means of the threaded nuts *n n*. On account of the large current to be carried, extra large contact surfaces are provided between switch blades and clips, as seen in the figure.

168. Feeder Regulators: Potential Regulators. When several feeder circuits are supplied from the same bus-bars, and when it is desired to control the voltage on each feeder circuit *independently* of the others, feeder regulators are required.

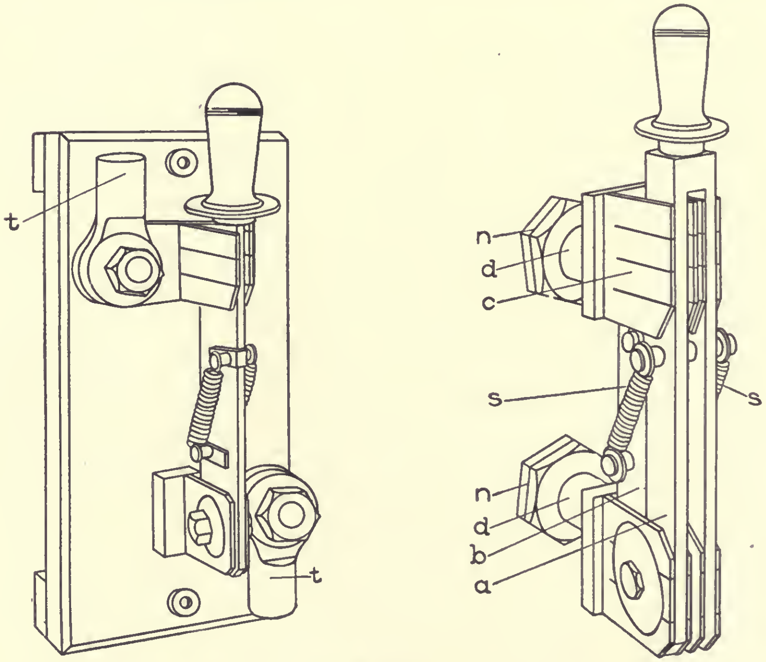


Fig. 350.

The single-phase feeder regulator is an auto-transformer with its primary coil connected across (that is as a shunt to) the bus-bars, and its secondary connected in series with the feeder circuit.

(*a*) In one type of feeder single-phase regulator (the Stillwell) the secondary coil has many leads brought out to points on a dial switch, so that the number of active turns on the secondary coil may be changed at will, thus permitting the adjustment of the feeder voltage to any desired value.

(*b*) In another type, the primary and secondary coils are wound at right-angles to each other on the inner face of a laminated iron ring very much like the stator ring of an induction motor. The magnetic flux, due to the primary coil, is made to pass *in whole or in part* through the secondary coil by turning a laminated core as explained below.

(*c*) Polyphase feeder-regulators usually consist of several single-phase regulators, one for each phase. The advantage of this arrangement is that the voltage of each phase may be controlled separately. A combined polyphase feeder regulator is, however, sometimes used.

(*a*) *The Stillwell Regulator.* Fig. 351 is a general view of a Stillwell single-phase voltage regulator with its dial switch complete. The dial switch alone is shown in Fig. 352. The complete internal connections are shown in Fig. 353. The primary coil of the regulator is permanently connected across the bus-bars (or generator terminals). One feeder wire passes out directly from the generator and the other passes through few, or many, turns of the secondary coil of the regulator, and thence to the line. The reversing switch A, serves to connect the feeder *f* to one or the other terminal of the secondary coil, and the arm of the dial switch connects the line wire to any one of the taps which are brought out from the secondary coil. For one position of the reversing switch, the induced voltage in the secondary turns, which are connected in series with the feeder circuit, is added to the generator voltage, thus raising the

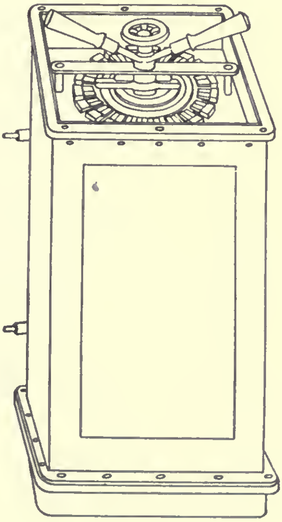


Fig. 351.

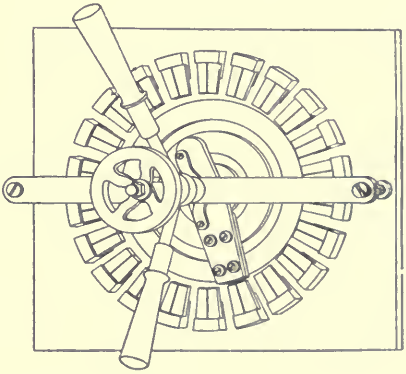


Fig. 352.

feeder voltage. For the other position of the reversing switch, the induced voltage in the secondary turns, which are in series with the feeder circuit, is subtracted from the generator voltage, thus reducing the feeder voltage.

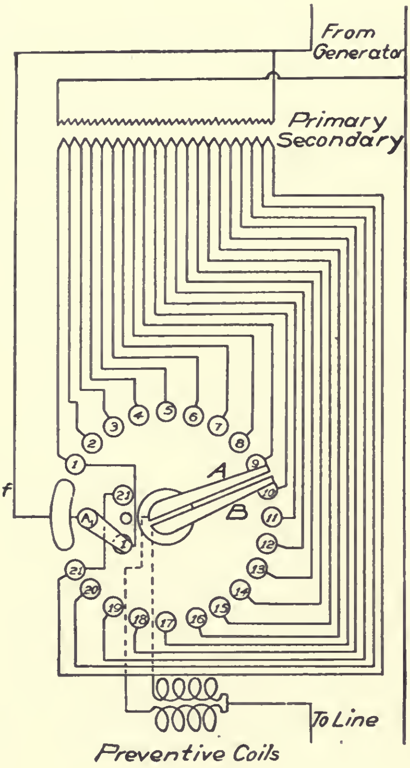


Fig. 353.

When the arm of the dial switch touches two adjacent contact points (and it must be arranged to always touch one point before it leaves the other), the intervening turn (or turns) of the secondary coil of the regulator is short-circuited. To overcome this difficulty, the arm is made double, that is, two arms A and B move together side by side as shown in Fig. 354. These arms are shown connected to two contact points, say 15 and 16. C represents a special form of choke coil consisting of two windings on one iron core. These two windings are arranged so that equal currents flowing out from A and B circulate around the core in opposite directions, so that the core is not magnetized, and the windings of C have no choking action. When, however, the two fingers A and B touch adjacent points of the dial switch, the turns of wire S on the regulator secondary tend to send a very large current out on A, let us say, and back on B. These oppo-

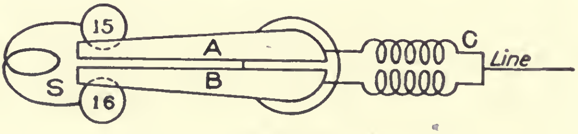


Fig. 354.

sitely flowing currents circulate around the core of C in the same direction. These currents, therefore, magnetize the core, and the windings of C have in consequence a very considerable choking action. The effect of the special choke coil C is to choke down oppositely flowing currents in the fingers A and B, and at the same time to allow currents flowing in the same direction in the fingers A and B to flow through it without any choking action.

(b) *The magnetic voltage regulator.* The type of voltage regulator mentioned under (b) above is sometimes called the magnetic voltage regulator. A laminated iron ring R R R R, Fig. 355, has four large deep slots on its inner face in which the primary coil P P and the secondary coil S S are placed. A laminated core C C mounted on a spindle is arranged to be turned into any desired position by means of a hand wheel. In the position indicated by full lines, the core carries the magnetic flux due to the primary coil in one direction through the secondary coil, and in the position indicated by dotted lines, the core carries the magnetic flux due to the primary coil in the other direction through the secondary coil. Therefore when the core is moved slowly from the position 1 to the position 2, in the direction indicated by the arrows, the voltage induced by the secondary coil changes gradually from a full positive value to an equal negative value in its relation to the primary voltage. That is, when the core is position No. 1, the induced voltage in the secondary coil has its greatest value of say, 100 volts which, if the coils are properly connected, is added to the bus-bar voltage E, giving a feeder voltage of E + 100. When the core is midway between the two positions 1 and 2, the induced voltage in the secondary coil is zero, and the feeder voltage is then equal to the bus-bar voltage E. When the core is in the position 2, the induced voltage in the secondary coil is again at its greatest

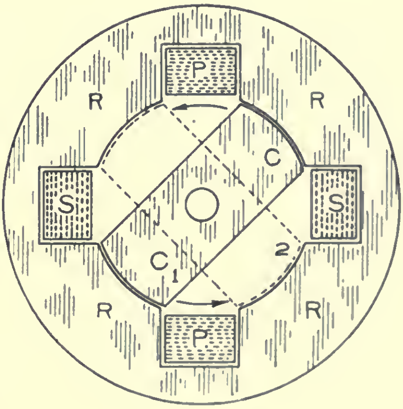


Fig. 355.

value of say, 100 volts, but in such a direction as to oppose the bus-bar voltage, so that the feeder voltage is E – 100 volts.

Fig. 356 is a view of a magnetic voltage regulator with the cover of its containing case removed. The two coils, primary and secondary, at right angles to each other, are clearly shown with their leads passing out to the connection board which occupies the compartment on the back of the case in the figure. The hand wheel for turning the iron core is also shown. A valuable feature of this type of regulator is that it produces a continuous variation of voltage, whereas the Stillwell regulator produces a step-by-step variation in the voltage.

(c) *The induction regulator.* The combination polyphase induction regulator is called the *induction regulator* from its similarity to the induction motor. The action of the induction regulator stated in simplest terms is as follows: A regular induction motor stator has its polyphase windings connected across the polyphase bus-bars. This produces a rotating magnetism in the stator iron as explained in article 137. This rotating magnetism rotates in synchronism with the generator or generators which are supplying current to the bus-bars. Inside of this induction motor stator (or primary) is placed a polyphase armature which does not revolve, but it is mounted on a spindle so that it may be turned through an angle of 60° or 90° by means of a hand wheel and worm gear. The rotating stator magnetism induces polyphase electromotive forces in the windings of this polyphase armature; these polyphase electromotive forces are in synchronism with the electromotive forces between the bus-bars, and the two (or more) windings of the polyphase armature are connected in series with the two (or more) feeder circuits (constituting

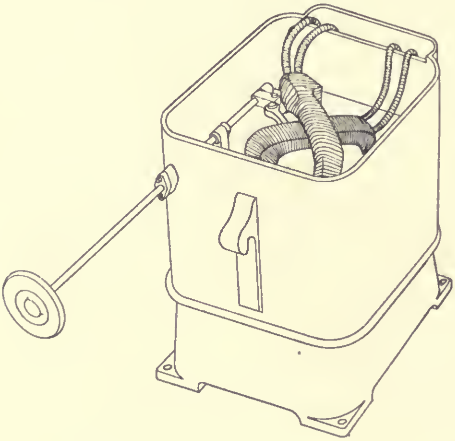


Fig. 356.

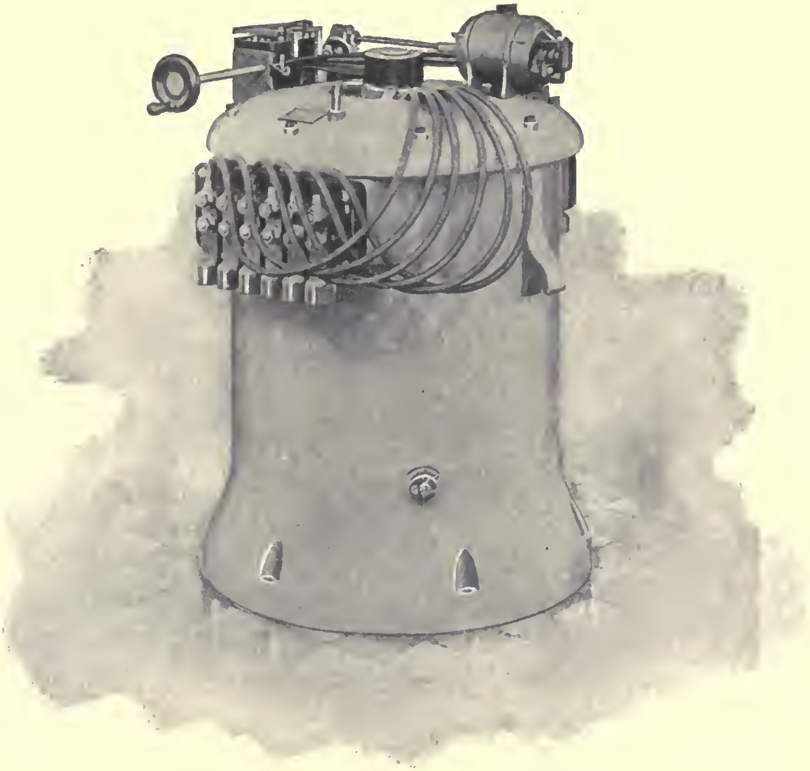


Fig. 357.

of course one set of polyphase feeders) which are to be regulated. The electromotive forces in the stationary armature windings may be in phase with the bus-bar electromotive forces, in which case the regulator raises the voltage by the greatest amount of which it is capable. By turning the stationary armature by means of the hand wheel and worm gear, the phase difference between the bus-bar voltages and the voltages induced in the stationary armature windings may be gradually changed from coincidence of phase to opposition of phase, during which time the boosting effect of the regulator will gradually drop to zero, become negative, and reach its greatest negative value when opposition of phase is reached. Thus if the electromotive force induced in each armature winding of the regulator is 100 volts, and if the bus-bar voltage is 1,000 (each phase), then the voltage between the feeders can be varied from 900 volts to 1,100 volts by means of the regulator.

Fig. 357 is a general view of a six-phase induction regulator in its containing case, manufactured by the General Electric Co. This particular machine has the primary windings on the movable member, whereas the armature windings are on the stationary member.

It is used for controlling the alternating-current voltages applied to the collector rings of a six-phase rotary converter. The figure shows a small direct-current motor mounted on the regulator case for turning the movable member of the regulator, this motor being controlled by the hand wheel shown in the figure.

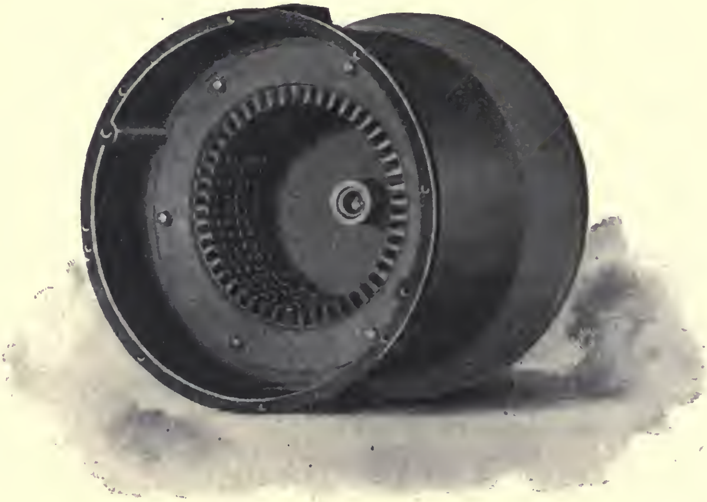


Fig. 358.

Fig. 358 shows the laminated iron core of the stationary member of an induction regulator, the stampings of which are clamped in a cast-iron shell. Fig. 359 shows the movable core.

Ratings of Voltage Regulators. It was pointed out in article 95, that the total amount of power delivered to service mains at a slightly increased voltage produced by an auto-transformer is very much greater than the power actually transformed from the primary to the secondary of the transformer. In fact the power actually transformed is equal to the increase (or decrease) of voltage multiplied by the total current delivered, and the rating of the auto-transformer (which determines its size) is based upon the power actually transformed.

Example. A voltage regulator is to be used for raising the voltage of 2,000-volt bus-bars to a maximum of 2,100 volts, and the maximum current to be handled is 100 amperes. In this case the transformer rating of the regulator is 100 amperes at 100 volts (or 10 kilowatts), whereas, the total power to be delivered to the feeders is, at its maximum, 2,100 volts × 100 amperes or 210 kilowatts.

Since a voltage regulator transforms only a small fraction of the power delivered to the feeders which it controls, the losses of power in the regulator are very small indeed. Thus the 10 kilowatt regulator above mentioned might have a total loss of 300 watts, which is 3 per cent of the power actually transformed by the regulator, and only one-seventh of one per cent of the total power delivered to the feeders.

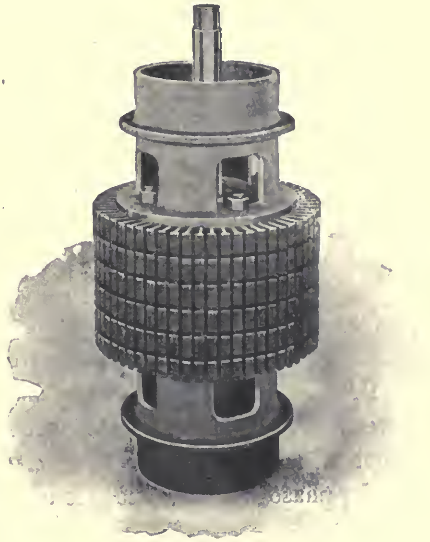


Fig. 359.

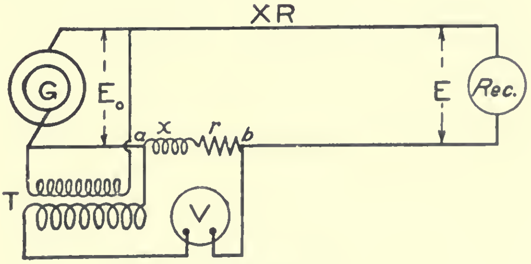
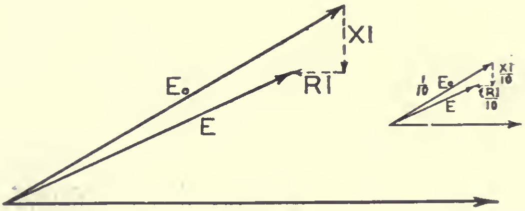


Fig. 360.

169. The Voltmeter Compensator is a device by means of which the voltmeter on the switchboard in a station is made to indicate the voltage between the transmission lines at some remote feeding center or receiving station. The essential principles of this instrument are:

An alternating-current generator G delivers alternating current at voltage E_0 between its terminals. This current is transmitted over a line of which the resistance is R (including r) and



Figs. 361 and 362.

the reactance is X (including x) and the voltage at the receiver is E. The line loss of electromotive force is XI due to reactance, and RI due to resistance as explained in article 26. The relation between E_0, E, RI and XI is shown in Fig. 361. T is a transformer which supplies to the voltmeter V a voltage which is exactly in phase with E_0, and, let us say, one-tenth as great. Let x

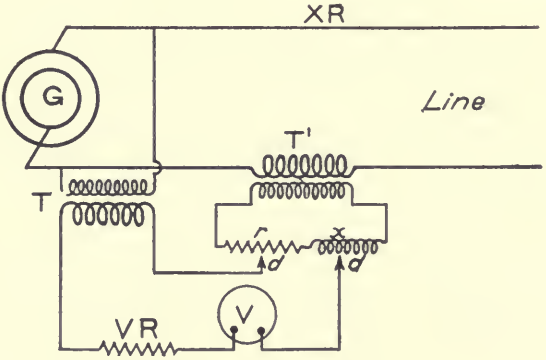


Fig. 363.

be a reactance one-tenth as great as X, and r a resistance one-tenth as great as R. Then the voltage between the points a and b consists of two parts, rI and xI, which are in phase with, and one-tenth as great as, RI and XI, respectively. Therefore rI and xI subtracted from one-tenth E_0 give a voltage which is exactly equal to, and in phase with, one-tenth E, as shown in Fig. 362, so that the voltmeter being acted upon by (one-tenth $E - rI - xI$) gives a reading which multiplied by 10 is equal to E.

In practice, it is not desirable to connect the voltmeter wires to the high-voltage mains, and the essential features of the arrangement shown in Fig. 360 are realized by introducing r and x in series with the secondary of a current transformer T^1, as shown in Fig. 363. More or less of the resistance r and of the reactance x may be included in the voltmeter circuit by means of two dial switches of which the arms are represented by *d d*, Fig. 363. The object of these dial switches is to enable a given compensator to be adjusted to any given transmission line.

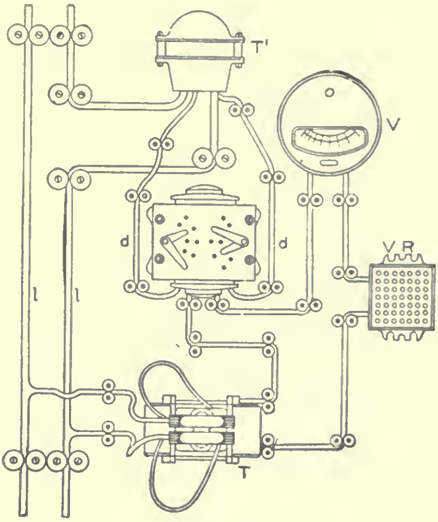


Fig. 364.

Fig. 364 shows all of the apparatus used in connection with the Westinghouse compensated voltmeter; the lines are shown at the left, *l*, *l*, T is the step-down potential transformer, T' is the series transformer, *d d* is the case containing the resistance r and the reactance x, and upon which the dial switches are mounted, V is the voltmeter, and VR is the resistance in series with the voltmeter.

LIGHTNING ARRESTERS.

170. Effects of Lightning. When a lightning stroke occurs in the neighborhood of a transmission line, a sudden rush of electric current takes place over the line due to one or more of the following causes :

(*a*) Electric charge accumulated on the line is suddenly released and tends to flow to earth.

(*b*) The magnetic action of the lightning discharge induces a sudden rush of current in the line.

(*c*) When the lightning discharge actually strikes the line, an enormous rush of current takes place over the line and to earth.

When the sudden rush of current which accompanies a lightning discharge encounters a portion of the circuit which has considerable inductance, very great electromotive forces are created, in the same way that enormous mechanical forces are created when a moving body strikes a heavy obstacle, and the insulation of the circuit, be it air or solid insulation, is likely to be broken down, or punctured, giving a short path to the earth for the rush of current. Thus a sudden rush of current coming into a station over a transmission line, encounters the highly inductive windings of wire of a transformer, dynamo, or other apparatus. The electrical inertia (inductance) of the windings dams up the rush of current, as it were, and the current rush is almost sure to break through the insulation at the very entrance to the winding, passing from the copper wire over to any metal which is connected more or less thoroughly to earth.

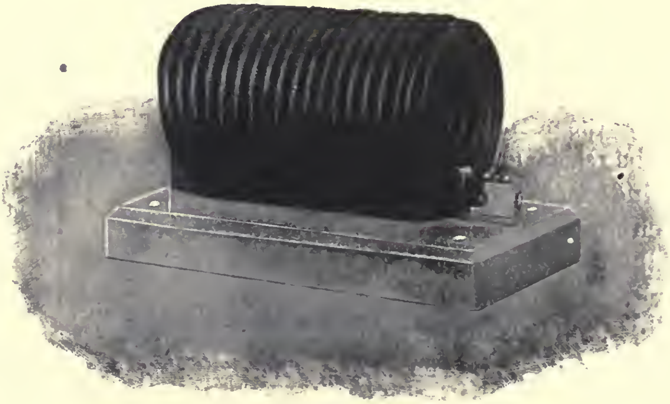


Fig. 365.

171. A Lightning Arrester is a device for shielding a transformer, dynamo, or other piece of apparatus from the rushes of current which come into a station on an overhead line during a thunderstorm.

The lightning arrester consists of:

(*a*) An inductance coil, or choke coil as it is called, for damming up more or less completely the rush of current before it reaches the dynamo or other apparatus.

(*b*) A weak place, specially arranged in the insulation of the line, that is, a spark gap, just in front of the choke coil through which the dammed up rush of current may break, and flow harmlessly to earth.

(*c*) A conducting path to earth as straight and direct as possible, and a good earth connection. Turns and bends in the conducting wire connected to earth, are to be avoided, inasmuch as they introduce inductance which tends to check the quick flow of current to earth.

(*d*) A device for extinguishing the electric arc which may be maintained across the spark gap by the regular line current itself, after the rush of current from the lightning discharge has passed and gone.

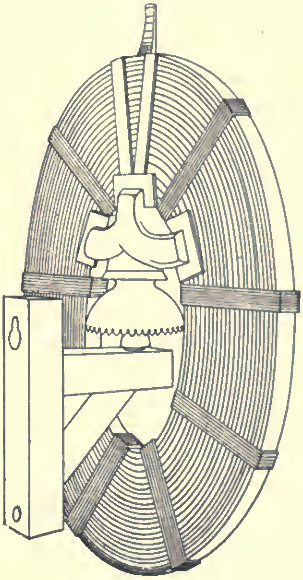


Fig. 366.

The choke coil of a lightning arrester must be very highly insulated. Two types of choke coil are commonly used. Fig. 365 shows a cylindrical choke coil mounted on a marble base, and consisting of three layers of large and very thickly insulated wire. The terminals of the coil are at its two ends. Fig. 366 shows a choke coil consisting of an insulated copper strip wound like a roll of tape. One terminal of this choke coil is on the outer edge and the other is at the center. The figure shows the method of supporting the coil on a special insulator carried on a bracket. Iron cores do not add to the damming action of a choke coil in the case of the excessively quick rushes of current which accompany lightning discharges, for the reason that the iron does not have time to become magnetized. Therefore lightning arrester choke coils are always made without iron cores.

The spark gap of alternating current-lightning arresters is usually made between massive blocks of metal. The effect of these massive blocks is to sufficiently cool the vapors of the arc, during the brief interval when the alternating current is nearly equal to zero, to prevent the passage of the next wave of alternating current. Thus an alternating electromotive force of a frequency of 60 cycles per second, and 500 volts (effective value), cannot maintain an arc across a $\frac{3}{64}$ inch air gap between massive blocks of brass. For higher voltages, two or more spark gaps are connected in series. Fig. 367 shows six spark gaps in series between seven massive brass cylinders mounted in a row between two porcelain supporting blocks. The end cylinders have bolts running through them which serve to clamp the porcelain blocks together, and also serve as electrical terminals L and G, which are to be connected to the line and to the ground (earth) respectively.

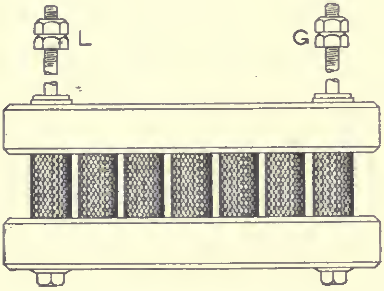


Fig. 367.

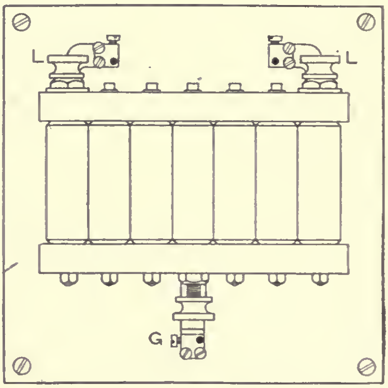


Fig. 368.

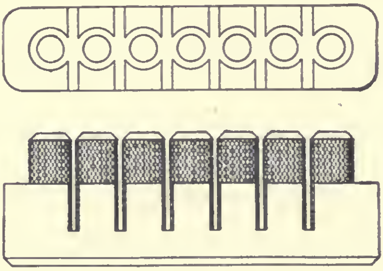


Fig. 369.

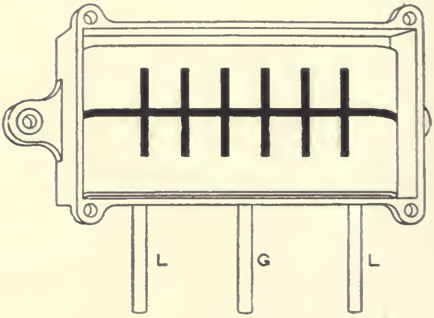


Fig. 370.

Fig. 368 shows a row of seven metal cylinders mounted on a marble base or panel. The middle cylinder has a ground connection G and the two end cylinders have binding posts L L for connecting to two lines.

This arrangement gives, therefore, three spark gaps in series between each line and the ground, which is sufficient to suppress a 1,000-volt arc.

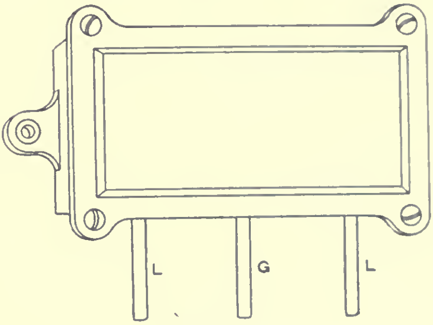


Fig. 371.

Figs. 369, 370, and 371, show the details of a double-pole lightning arrester for outdoor use. The metal cylinders are held in place by porcelain blocks which fit in a water-tight containing case, and the arrester is thus suitable to be installed on a pole or other location exposed to the weather.

Fig. 372 shows the method of connecting Westinghouse arresters for protecting two line wires. For 1,250-volt lines, three spark gaps between each line and ground are sufficient. For 2,500 volts, six spark gaps between each line and ground are required. If choke coils are used they are connected in circuit at the points

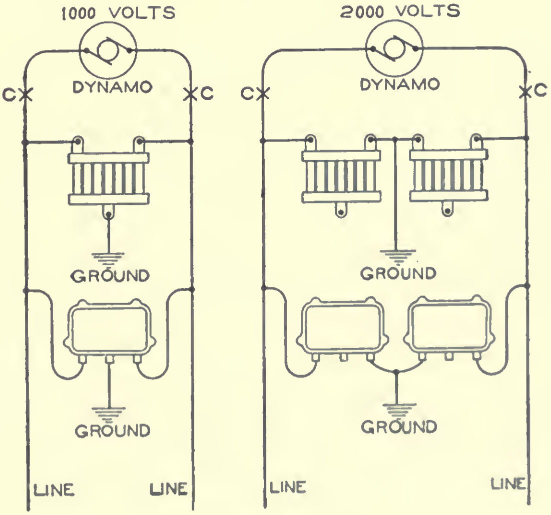


Fig. 372.

marked C C C C. Frequently choke coils are not used, in which case the dynamo or transformer itself chokes the rush of current, and the insulation on the dynamo or transformer must be considerably stronger, electrically, than the series of air gaps in the path from the line through the arrester to ground.

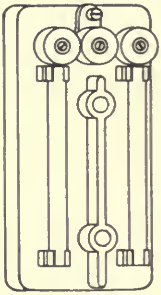


Fig. 373.

Use of resistance in series with the spark gaps. When a lightning discharge breaks down the spark gaps between both lines and earth, or when one line is already grounded and the lightning discharge breaks down both gaps between the other line and earth, a very great current flows from the dynamo across the gaps from line to line, on account of the low resistance of the spark gaps when once broken down by a spark. This great flow of current may be prevented by a resistance connected in series with the spark gaps; and if this resistance is as nearly non-inductive as possible, it has no serious effect in retarding the flow of the lightning discharge to earth. The advantage of this resistance is that, with the smaller current from the dynamo which follows the lightning discharge, the cooling effect of the massive metal cylinders can more easily and surely suppress the arc. The practice of the General Electric Co. is to use this series resistance in all their alternating-current arresters, even for 1,000 or 2,000 volts, while the Westinghouse Co. uses the series resistance only for much higher voltages. When the series resistance is used, the number of spark gaps in series required to suppress the arc is less than when the resistance is not used.

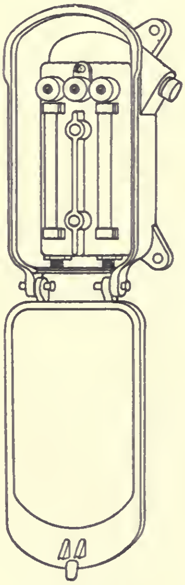


Fig. 374.

Fig. 373 shows a double-pole lightning arrester for a 1,000-volt circuit mounted on a porcelain block, and Fig. 374 shows the same arrester enclosed in a water-tight case for outdoor use. This 1,000-volt double-pole arrester consists of three short brass cylinders shown at the top in Figs. 373 and 374, the middle cylinder being connected to ground, and the two side cylinders to the respective lines through non-inductive resistances made of rods of graphite. These rods are the vertical rods shown in Figs. 373 and 374. There is, therefore, one spark gap and a graphite resistance between each line and the ground. Fig. 375 shows the manner of connecting one double-pole 1,000-volt arrester, marked 1,000-V D P, or two single-pole 1,000-volt arresters (marked 1,000 V S P), to the two lines *l*, *l*, of a 1,000-volt alternator. The choke coils or reactance coils are indicated by the two spirals next to the alternator, and the ground connection is at G.

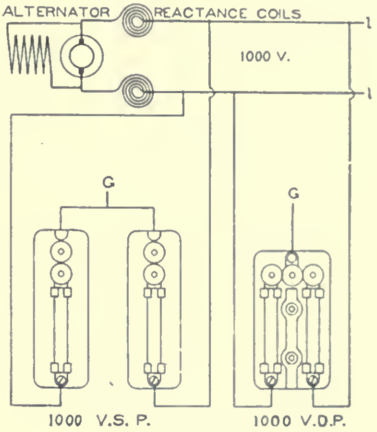


Fig. 375.

Fig. 376 shows the manner of connecting one double-pole 2,000-volt arrester (marked 2,000 V D P), or two single-pole 1,000-volt arresters (marked 2,000 V S P) to the two lines *l*, *l*, of a 2,000-volt alternator. This 2,000-volt arrester has two spark gaps between each line and the ground, as may be seen by carefully studying Fig. 376.

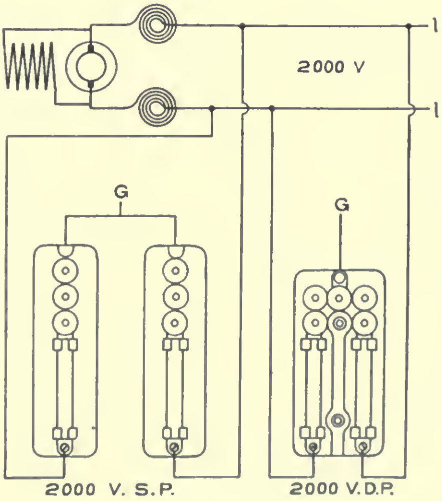


Fig. 376.

Arresters for very high voltages are made by connecting low-voltage arresters in series. Thus Fig. 377 shows two double-pole 2,000-volt arresters connected as single-pole arresters to the two lines *l*, *l*, of a 3,000-volt alternator. This places the four spark gaps and the two graphite resistances of each arrester in series between each line and the ground. Fig. 378 shows eight double-pole 2,000-volt arresters connected in series in two sets of four arresters each, to protect a 10,000-volt line, *l*, *l*. Each set serves as a single-pole arrester giving sixteen spark gaps and eight graphite resistances in series between each line and the ground.

Fig. 379 shows two arrester units of six spark gaps each, arranged as a single-pole arrester to protect one line wire of a pair of 6,000-volt mains. At the very beginning of the lightning discharge, the six spark gaps of A, only, have to break down, then, perhaps one ten-millionth part of a second later, the current through the series gaps of A and the "shunt resistance" becomes sufficiently great to cause the break down of the shunted gaps B, when the current rush flows to earth through the comparatively low "series resistance". As the current rush dies away, the arcs in the shunted gaps are suppressed first, because of the fact that the "shunt resistance" takes a considerable portion of the current, and the arcs in the series gaps are suppressed afterwards.

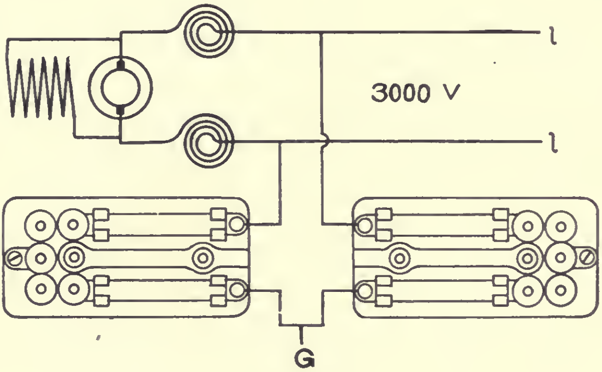


Fig. 377.

172. The Combination of a Condenser with a Choke Coil. The choking action of a coil of wire is due to its electrical inertia or inductance, and the shielding of the apparatus behind a choke coil from severe electrical strains is precisely analogous to the following mechanical arrangement :

A wall is shielded from the severe strains due to a hammer blow by allowing the hammer to strike against a very heavy ball of iron which rests against the wall. The completeness with which this heavy iron ball shields the wall depends upon the interposing of an elastic substance between the ball and the wall. The ball alone cannot shield the wall unless the wall itself is slightly elastic. The completeness with which a choke coil shields the dynamo and other apparatus depends upon the presence of some electro-elasticity*, or capacity in the circuit behind the choke coil. In some cases the circuit behind the choke coil has sufficient capacity for this purpose; it is always best, however, to connect a condenser behind the choke coil as shown in Fig. 380.

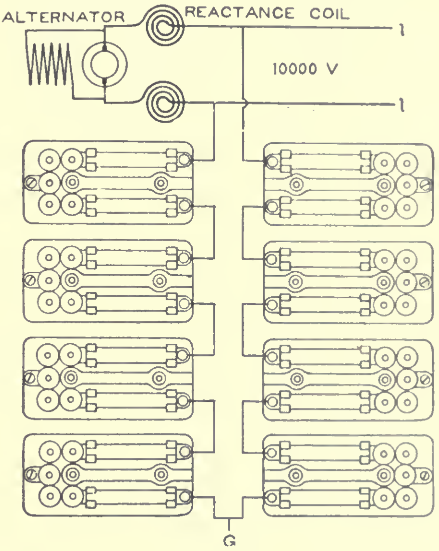


Fig. 378.

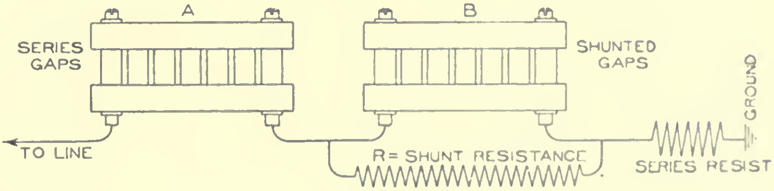


Fig. 379.

The choke coil and condenser are immersed in an oil tank when installed. From Fig. 380 it is seen that three wires *b b b* connect to choke coil and condenser. This combination of choke coil and condenser is called a "static interrupter" by the Westinghouse Company.

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* See article 6.

INSTRUCTIONS FOR INSTALLING LIGHTNING ARRESTERS.

173. Location of Arrester. As regards the location of lightning arresters, electric plants may be divided into two groups :

(*a*) Plants in which the individual pieces of apparatus such as transformers, motors, arc lights, etc., are many in number and widely scattered. In these cases lightning arresters should be located for the purpose of protecting the whole line. They should be located at a number of points, more numerous on the parts of the line particularly exposed, and fewer in number on the parts that are naturally protected, especially those parts shielded by tall buildings or numerous trees. No definite statement can be made as to the number of arresters needed per mile, as the requirements of different cases vary widely. Frequently in this sort of plant, choke coils are not used on circuits not exceeding 2,500 volts.

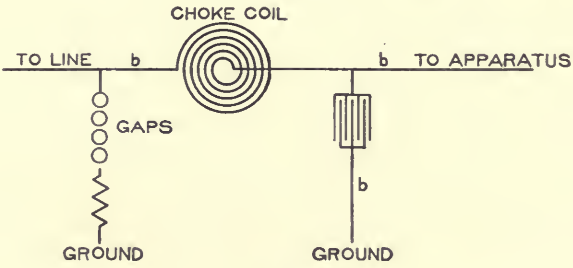


Fig. 380.

(*b*) Plants in which the apparatus is located at a few definite points in the system, as in a high-voltage transmission line. In such cases the arresters should in general be located to protect especially those points where apparatus is situated—that is, should be placed with the object of protecting the apparatus rather than the line as a whole.

The lightning arrester should always be so connected that in passing from the line to the apparatus the arrester is reached first, the choke coil second, and the condenser, if one is used, third.

Insulation. On account of its nature, a lightning arrester is evidently exposed to severe potential strains, consequently all live parts must be well insulated. On arresters for low voltages it is not a difficult matter to secure proper insulation, as the construction of the arrester itself affords protection. On high-voltage arresters, however, proper insulation is a more difficult matter. All arresters are marble or porcelain mounted, the marble or porcelain serving as an insulating support for the arrester. On circuits exceeding 5,700 volts, to obtain further insulation, the marble or porcelain bases should be mounted on wooden supports, well dried and shellaced. For 18,000 volts and above, the bases or panels should receive additional insulation from porcelain or glass insulators used as supports.

Two high-voltage arresters attached to different line wires should not be placed side by side without either a barrier or a considerable space between them.

Grounds. Too much importance cannot be attached to the making of proper connections to ground. The wire to ground should be as short and straight as possible.

It is obvious that a poor ground connection will render ineffective every effort made with choke coils and lightning arresters to drive the lightning discharge to earth. It is, therefore, important to construct a good ground connection.

A good ground connection for a bank of station arresters may be made in the following manner:

> First, dig a hole four feet square directly under the arrester until permanently damp earth has been reached; second, cover the bottom of this hole with crushed charcoal (about pea size); third, over this lay 10 square feet of No. 16 tinned copper plate; fourth, solder the ground wire, preferably No. 0 copper, securely across the entire surface of the ground plate; fifth, cover the ground plate with crushed charcoal; and, sixth, fill the hole with earth, using running water to settle.

The above method of making a ground connection is simple, and has been found to give excellent results, and yet, if not made in proper soil, it will prove of little value. Where a mountain stream is conveniently near it is not uncommon to throw the ground plate into the bed of the stream. This, however, makes a poor ground connection, owing to the high resistance of the pure water and the rocky bottom of the stream. Clay, even when wet, rock, sand, gravel, dry earth, and pure water are not suitable materials in which to bury the ground plate of a bank of lightning arresters. Rich soil is the best. It is therefore advisable, before installing a bank of choke coils and lightning arresters, to select the best possible site for the lightning arrester installation, with reference to a good ground connection. This may often be at some little distance from the station, in which case it is, of course, necessary to construct a lightning arrester house. Where permanen dampness cannot be reached it is recommended that water be supplied to the ground through a pipe from some convenient source.

When possible, a direct connection to an underground pipe system, especially of town or city water mains, furnishes a very excellent ground on account of the great surface in contact with the earth and the numerous paths for the discharge. In a water-power plant the ground should always include a connection to the pipe line or penstock.

Inspection. As the effectiveness of the arrester is of great importance, it should be inspected from time to time and the resistances and earth connection tested for open circuit.

REVIEW QUESTIONS.

PRACTICAL TEST QUESTIONS.

In the foregoing sections of this Cyclopedia numerous illustrative examples are worked out in detail in order to show the application of the various methods and principles. Accompanying these are examples for practice which will aid the reader in fixing the principles in mind.

In the following pages are given a large number of test questions and problems which afford a valuable means of testing the reader's knowledge of the subjects treated. They will be found excellent practice for those preparing for College, Civil Service, or Engineer's License. In some cases numerical answers are given as a further aid in this work.

REVIEW QUESTIONS

ON THE SUBJECT OF

ALTERNATING CURRENT MACHINERY.

PART I.

1. Explain the term "apparent watts."

2. What is the inductivity of a dielectric, and how is it determined?

3. Explain, with diagram, the method of adding two synchronous harmonic electromotive forces or currents.

4. Draw a curve of alternating current, electromotive force, and power in case the current lags nearly 90° behind the electromotive force.

5. Explain inductance.

6. For a given per cent of line loss in the transmission of a certain amount of power, what is the effect of making the voltage four times as great—(*a*) on the current? (*b*) on the resistance of line? (*c*) on the diameter of wire? (*d*) on the weight of wire? (*e*) on the cost of line?

7. If an alternator has 12 poles and is to give a frequency of 25, what must be its speed?

8. What is an exciter? Explain its function.

9. Define alternator alternating electromotive force, and alternating current.

10. What determines the difference between the generator electromotive force and the receiver electromotive force, (*a*) when the receiving circuit is non-reactive? (*b*) when the receiving circuit is highly reactive? (*c*) when the receiving circuit has large capacity reactance?

REVIEW QUESTIONS

ON THE SUBJECT OF

ALTERNATING CURRENT MACHINERY.

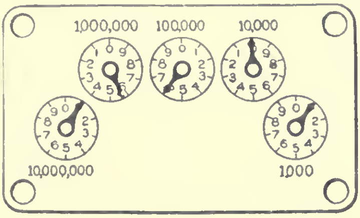
PART II.

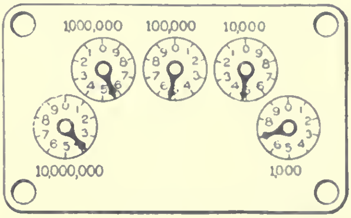
---

1. Is the three-ammeter method used in practice?

2. What is the necessity of a starting coil in the Thomson recording wattmeter?

3. In the two accompanying meter dials, give the reading in watt-hours and calculate the customer's bill.





4. Give the simplest method of determining the inductance of an armature, with the proper formula.

5. An alternator gives 1,000 volts between its collector rings at full load current and field excitation; when the armature current is decreased to zero, it gives 1,050 volts. What is the regulation?

6. What discovery made possible the use of polyphase currents for power purposes, through the medium of the induction motor?

7. How is the E.M.F. measured in the break-down test? Describe the apparatus used.

8. Supposing the power of a single-phase alternating-current circuit as measured by a wattmeter is 450 watts, and the

power factor is .82 while the voltage is 1,000, what current is taken from the mains?

9. Explain the effect of armature reaction upon the magnetic flux in case the armature current is in phase with the electromotive force, in case it lags behind the electromotive force, and in case it leads the electromotive force.

10. What methods are used in the field excitation of alternators?

11. In what way did the single-phase system fail to fulfill all the requirements for general purposes?

12. For an alternating current of a given frequency and wave shape how should a plunger type voltmeter be calibrated?

13. How is the speed of the Thomson recording wattmeter made proportional to the driving torque?

14. Give the fundamental equation of the alternator and explain the meaning of the symbols.

15. What do you understand by the regulation of an alternator?

16. Why is the three-voltmeter method not used in practice?

17. Using the price chart in Fig. 84, determine what will be charged for 86,500 watt-hours at 10 cents per thousand.

18. Which has the greater inductance; an armature with concentrated winding, or an armature with a distributed winding? Why?

19. What is meant by the synchronous reactance of an armature?

20. How does the inductance of an armature alternator vary with its linear dimensions?

21. Explain the Thomson inclined coil meter.

22. In the three-phase star-connected alternator, what is the relation between the electromotive force across the terminals of any given winding and the electromotive force between the mains?

23. Describe the two methods of constructing field coils for revolving field machines used by the General Electric Co.

24. What do you understand by the two-phase four-wire system?

REVIEW QUESTIONS

ON THE SUBJECT OF

ALTERNATING CURRENT MACHINERY.

PART III.

1. Explain why the armature windings are utilized to only $\frac{1}{2}$ the extent in the inductor alternator that they are in the ordinary alternator.

2. Mention the different causes of losses in alternating-current machines.

3. What is meant by synchronous impedance and what relation does the synchronous impedance curve show?

4. Explain what is meant by a fly-wheel alternator and give an example of the same.

5. Explain clearly the inductor alternator, and how it differs from the regular type of alternator.

6. Mention briefly the different methods of starting a synchronous motor, both single-phase and polyphase.

7. Theoretically what relation exists in the transformer between the primary and secondary electromotive force and the number of turns of each coil? Express this as a formula.

8. Explain the principles of operation of the synchronous motor.

9. Describe the type of generating unit used in the Manhattan power station.

10. What are the standard frequencies used with S. K. C. alternating current generators?

11. What do you understand to be meant by the term *windage?*

12. Outline briefly the method of performing the heat test on a generator.

REVIEW QUESTIONS

ON THE SUBJECT OF

ALTERNATING CURRENT MACHINERY.

PART IV.

1. In the mesh connection of transformers, if one coil is cut out, what per cent of the total power capacity remains?

2. If in a given transformer the voltage is increased 50%, how will this affect the eddy current and hysteresis loss?

3. What considerations prevent the action of the actual transformer from agreeing exactly with that of the ideal transformer?

4. When current is generated as two-phase, what is the object of changing it to three-phase when it is stepped up for long-distance transmission?

5. What can you say of the regulation of constant-current transformers as compared with that of constant-potential transformers?

6. What do you understand by a three-ring rotary converter?

7. Describe with sketch the method of testing for proper connection of secondaries to be connected in parallel to supply current to a given receiving circuit.

8. If the electromotive force between any two rings of a three-ring rotary converter is 500, what will be the direct-current voltage?

9. Without referring in any way to the book, show sketches of proper and improper connections of transformers, both in parallel and in series.

10. If the output of a 3 K.W. transformer is increased to 5 K.W., how does this affect the core loss?

REVIEW QUESTIONS

ON THE SUBJECT OF

ALTERNATING CURRENT MACHINERY.

PART V

1. When a rotary converter is self-started as an alternating-current motor, what precaution must be taken in regard to the polarity before connecting several rotaries to common bus-bars?

2. Why should there be very little, if any, series field winding provided on a machine to be run as an inverted rotary converter?

3. What factors enter into modifying the theoretical voltage ratios in actual rotary converters?

4. Is hunting more troublesome when the field of a motor is over-excited, or when it is under-excited?

5. Show sketch of method of supplying direct current to the Edison three-wire system with only a single machine.

6. In making a heat run on a rotary converter, what data should be taken and recorded?

7. Mention the different methods of starting a single-phase induction motor.

8. What effect does the load upon a rotary converter have upon the amount of pulsation or hunting?

9. In the case of a two-ring converter if the effective value of the alternating current flowing in at each collector ring is 150, what will be the direct current delivered by the converter?

10. What do you understand by an inverted rotary converter?

11. Name the principal tests that should be made upon rotary converters?

REVIEW QUESTIONS

ON THE SUBJECT OF

ALTERNATING CURRENT MACHINERY.

PART VI.

1. With a synchronous motor it is possible under certain circumstances to cause the current to lead the E.M.F. Is this possible with the induction motor?

2. Describe the most convenient method of obtaining the output of an induction motor in testing it for efficiency?

3. Give an expression for the apparent input in watts for the induction motor.

4. What precautions must be taken when operating compound alternators in parallel?

5. What do you understand to be meant by feeder panels?

6. If the voltage is 220 and the current 150. what is the apparent input in the case of a three-phase induction motor?

7. If the power factor of the above motor is .85 what is the actual input in watts?

8. Why cannot the core-loss test be performed on an induction motor by the method used in the case of a synchronous motor?

9. Describe the method of performing the slip test on an induction motor.

10. What are the disadvantages of slate as an insulator?

11. How are voltage regulators rated?

12. Describe the double-pole quick-break generator switch, manufactured by the Ft. Wayne Co., and explain the use of the marble barrier.

13. Explain the method of cutting out an alternator which is running in parallel with others.

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